Electromagnetic and Electromechanical Engineering Principles
Notes 03
Basic Machines

Marc T. Thompson, Ph.D.
Thompson Consulting, Inc.
9 Jacob Gates Road
Harvard, MA 01451
Phone: (978) 456-7722
Email: marctt@thompsonrd.com
Website: http://www.thompsonrd.com

Portions of these notes reprinted from *Fitzgerald*, Electric Motors, 6th edition

Course Overview --- Day 3

3	**<u>Basic machines</u>**		
	- Finish forces and torques with demo and 2 examples............................	7:30-8:30	1-24
	- Introduction to AC and DC machines..	8:30-9:30	25-41
	- Morning break..	9:30-9:45	
	- MMF of windings; rotating magnetic fields in rotating machinery; generated voltage..	9:45-11:00	42-76
	- Synchronous machines..	11:00-12:00	77-97
	- Lunch	12:00-1:00	
	- Linear and PM synchronous machines..	1:00-1:30	98-108
	- Induction machines..	1:30-2:45	109-133
	- Afternoon break..	2:45-3:00	
	- Finish induction machines..	3:00-3:30	134-149
	- Induction (eddy current) brakes...	3:30-4:00	150-178
	- Summarize..	4:00-4:15	179, various

Electrodynamic Levitation Demo

- AC levitation with 60 Hz excitation from autotransformer

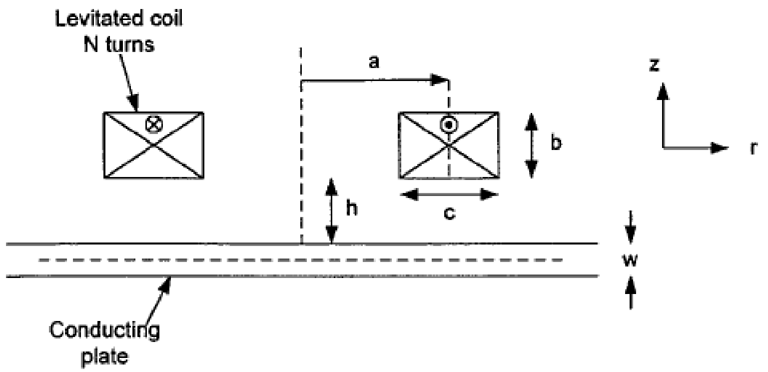
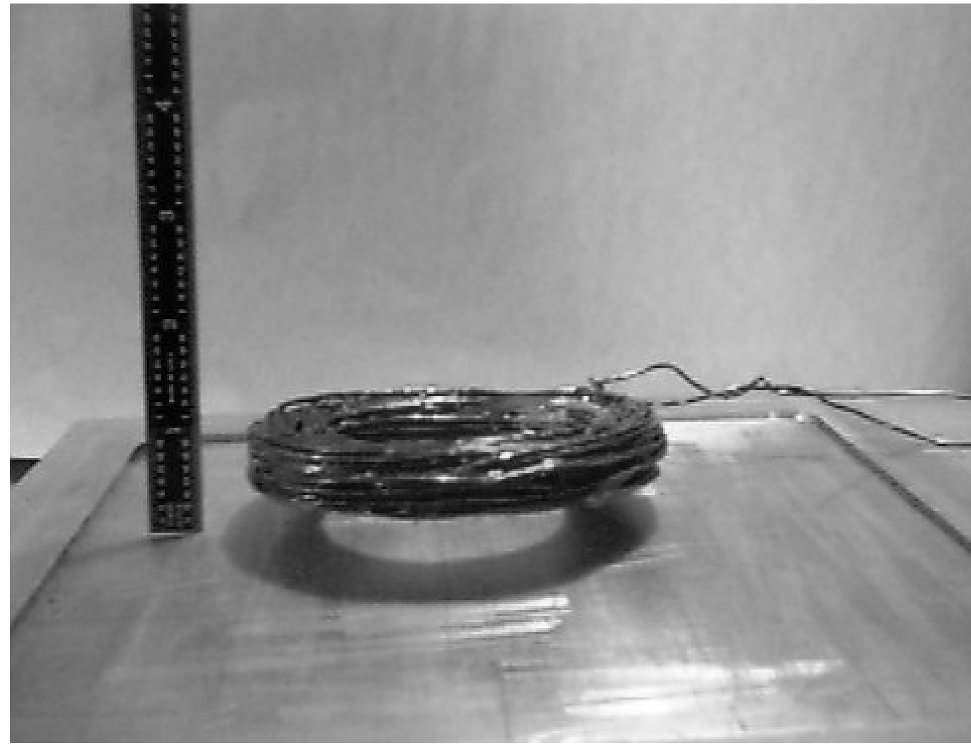


Fig. 1. Levitation experiment showing coil levitated electrodynamically above a conducting plate.



Reference: Marc Thompson, “Electrodynamic Magnetic Suspension --- Models, Scaling Laws and Experimental Results,” *IEEE Transactions on Education*, vol. 43, no. 3, August 2000, pp. 336-342

One Method to Calculate Lift Force

- We can deduce force acting on the coil by making measurement of inductance of coil at different heights

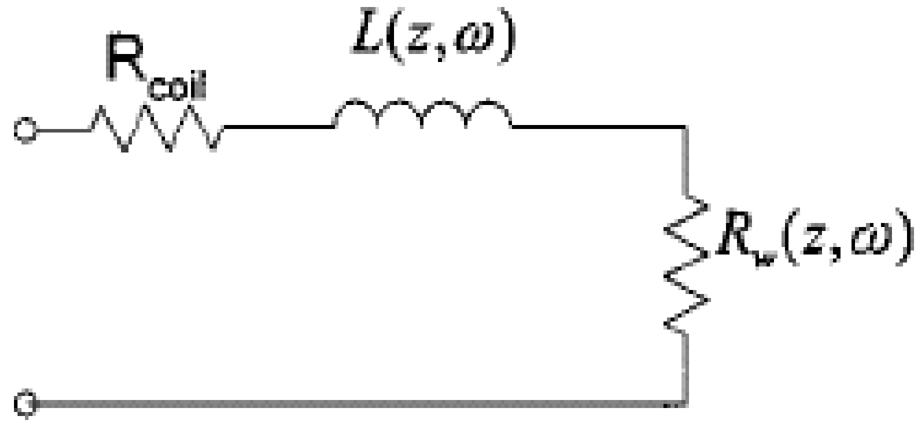


Fig. 2. Electrical model of system

Levitation Example

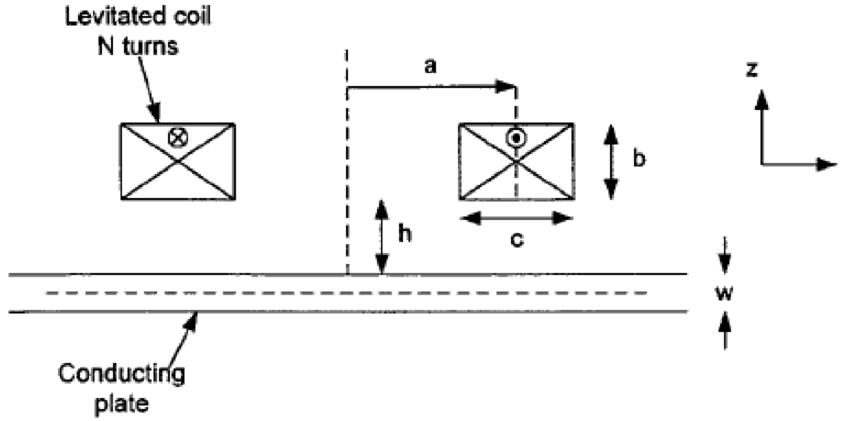


Fig. 1. Levitation experiment showing coil levitated electrodynamically above

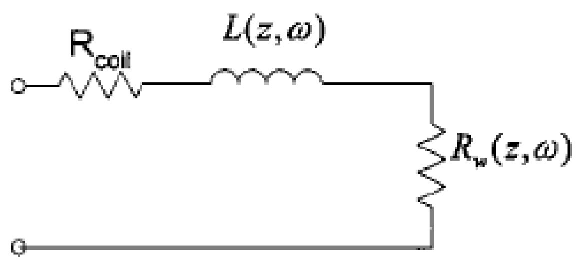


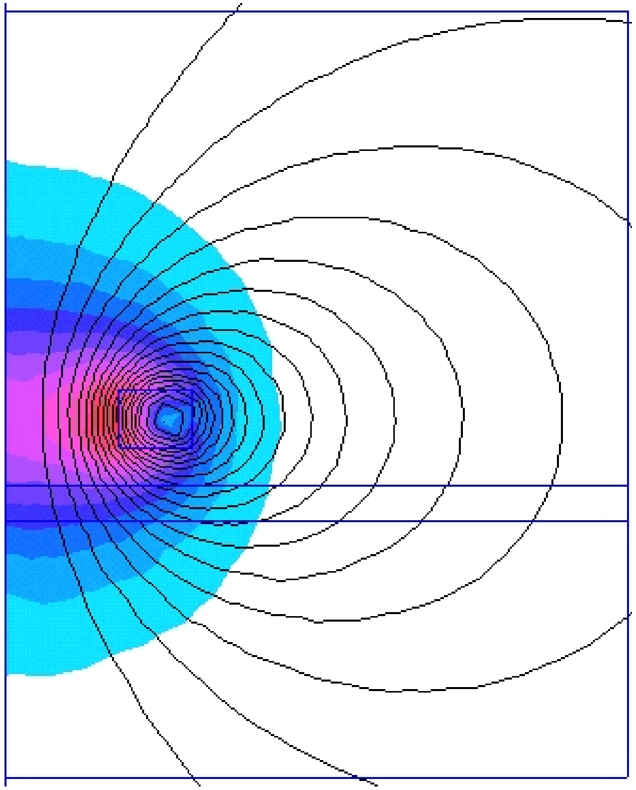
Fig. 2. Electrical model of system

Reference: Marc Thompson, "Electrodynamic Magnetic Suspension --- Models, Scaling Laws and Experimental Results," *IEEE Transactions on Education*, vol. 43, no. 3, August 2000, pp. 336-342

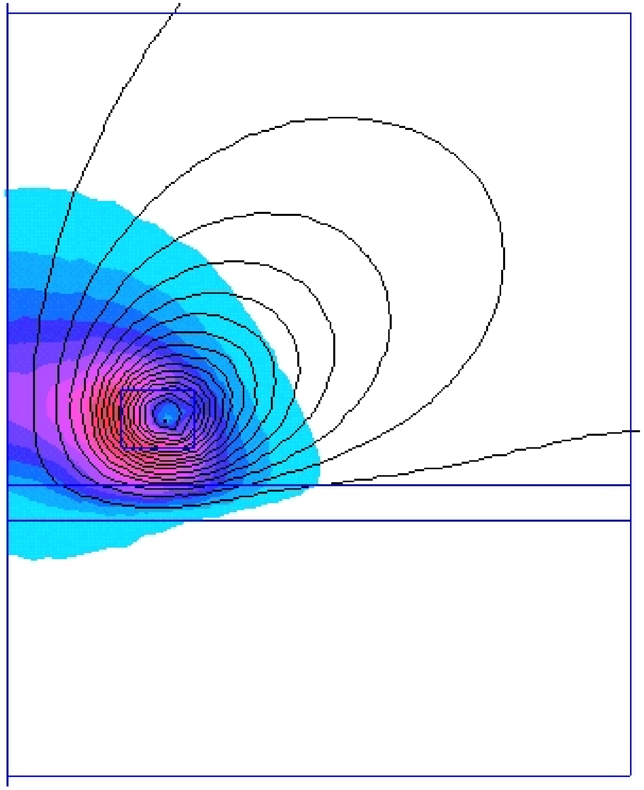
Circular Coil Above Conducting Aluminum Plate

- Flux density plots at DC and 60 Hz via FEA
- At 60 Hz, currents induced in plate via magnetic induction create lift force

DC



60 Hz



Levitation Example

- Coil inductance vs. coil height above aluminum plate at 60 Hz

$$L(z) \approx L_o - L_r(\omega)e^{((-z)/\gamma)}.$$

TABLE II
CURVE FIT PARAMETERS FOR TERMINAL INDUCTANCE

L_o	980 μH
L_r	280 μH
γ	20 millimeters

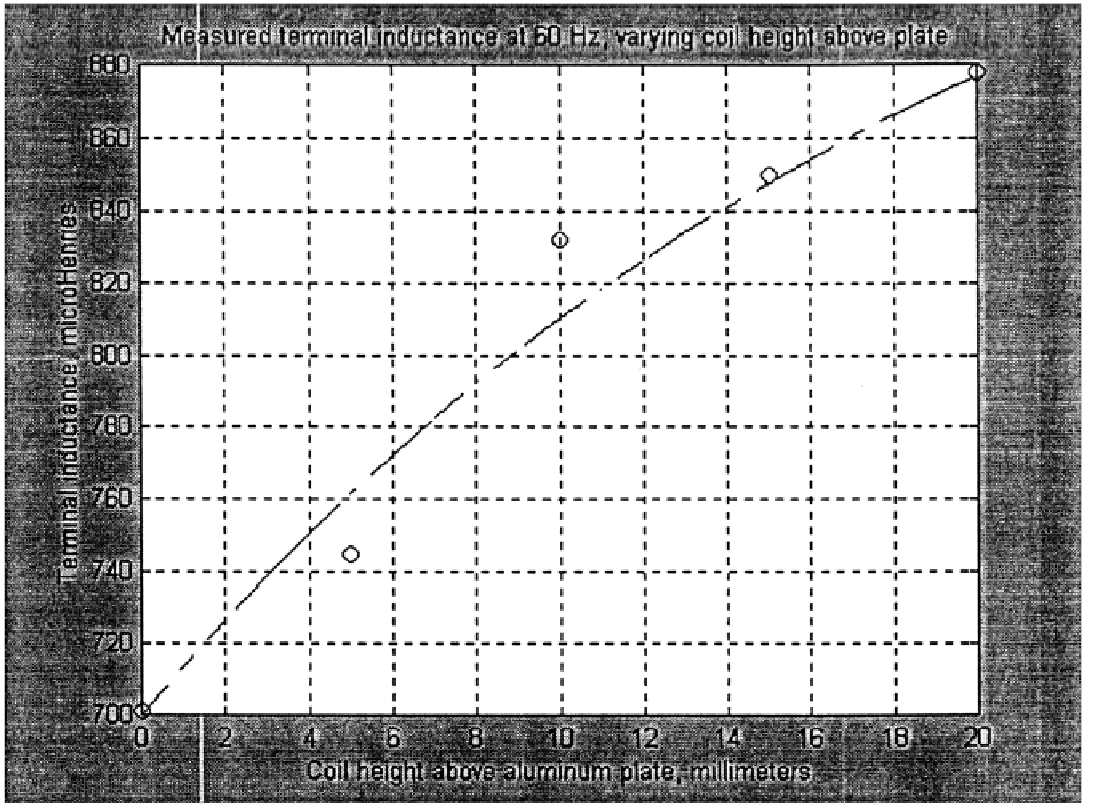


Fig. 5. The 60 Hz coil inductance for various coil heights above aluminum plate. Dotted line is curve fit to data.

Reference: Marc Thompson, "Electrodynamic Magnetic Suspension --- Models, Scaling Laws and Experimental Results," *IEEE Transactions on Education*, vol. 43, no. 3, August 2000, pp. 336-342

Levitation Example

- Curve fit for inductance: $L(z) \approx L_o - L_r(\omega)e^{((-z)/\gamma)}$.

- Magnetic stored energy: $E_m = \frac{1}{2}L(z)I^2$.

- Levitation force: $f_z = -\frac{d}{dz}E_m = \frac{I^2}{2}\frac{dL(z)}{dz} = \frac{I^2}{2\gamma}L_r e^{(-z)/\gamma}$.

TABLE II
CURVE FIT PARAMETERS FOR TERMINAL INDUCTANCE

L_o	980 μH
L_r	280 μH
γ	20 millimeters

Reference: Marc Thompson, "Electrodynamic Magnetic Suspension --- Models, Scaling Laws and Experimental Results," *IEEE Transactions on Education*, vol. 43, no. 3, August 2000, pp. 336-342

Levitation Example

TABLE III
PREDICTED AND ACTUAL COIL CURRENT VS. LEVIATION HEIGHT, AND CALCULATED POWER DISSIPATION IN COIL

h (mm)	$I_{measured}$ (A-RMS)	I_{calc} (A-RMS)	Q (Watts)
0	21	22.1	168
10	26	28.4	257
20	39	36.5	578

Reference: Marc Thompson, "Electrodynamic Magnetic Suspension --- Models, Scaling Laws and Experimental Results," *IEEE Transactions on Education*, vol. 43, no. 3, August 2000, pp. 336-342

AC Magnetic Suspension Scaling Laws

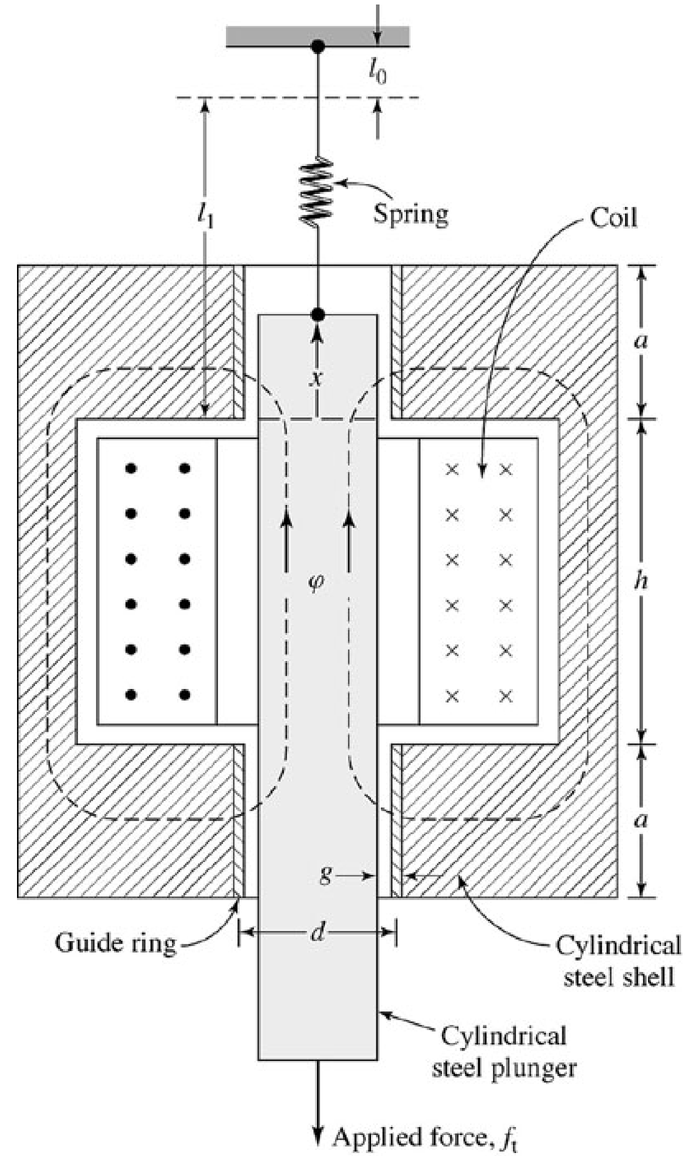
- Scaling law for zero speed EDS

$$P \propto M^{\frac{2}{3}}$$

- Coil mass M = 0.35 kg; P = 257 W at h = 10 mm
- Full scale suspension: For M = 1000 kg, P = 51 kW
- Other tradeoffs:
  - Excitation frequency vs. guideway thickness

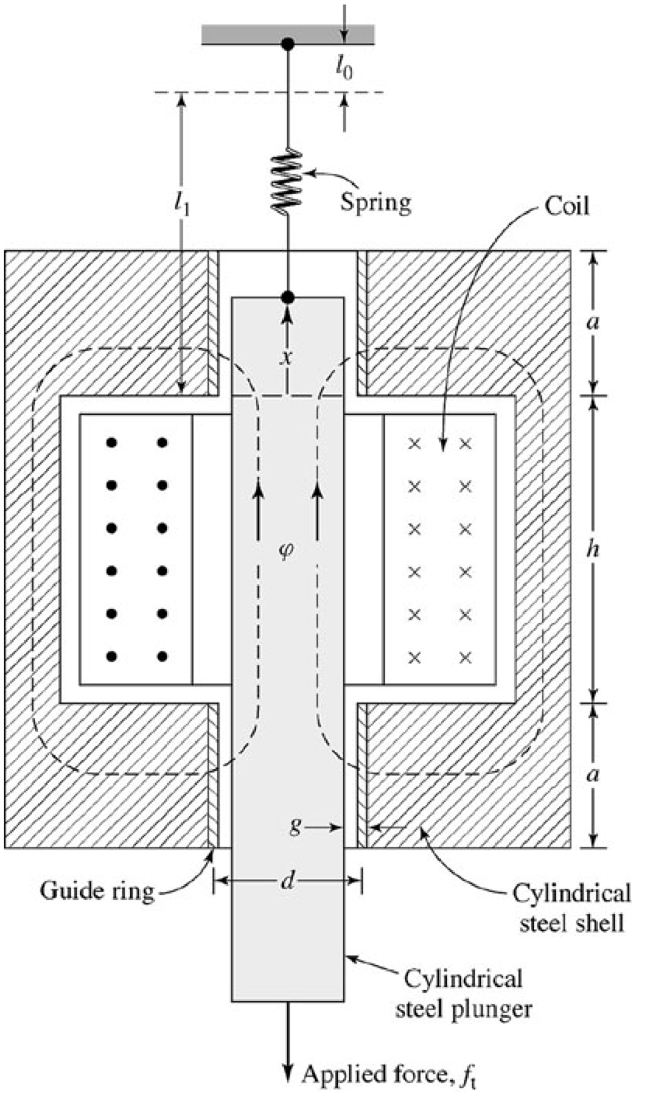
Example and Case Study: Solenoid Design

- Follows Example 3.10 in *Fitzgerald* (pp. 153-155)
- Note that dimension x is the distance from the top of the plunger to the top of the coil
- As this dimension x varies, axial force on the plunger varies as well



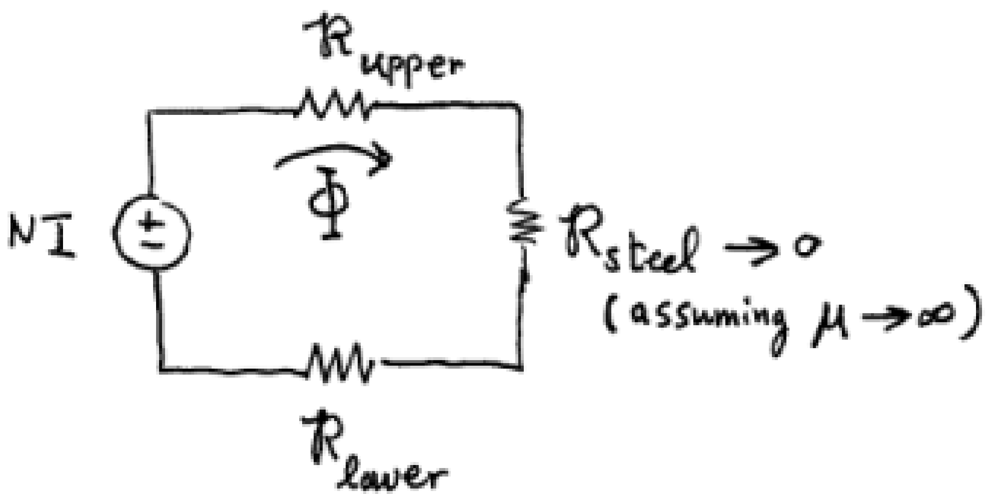
Strategy

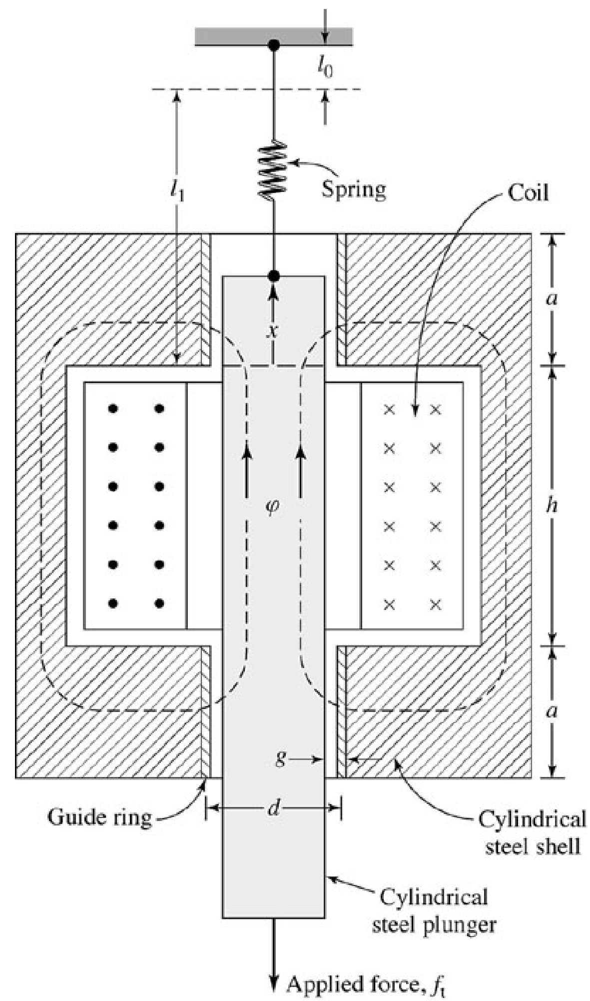
- Use reluctance model
- Find flux Φ
- From flux, find flux linkage λ
- From flux linkage, find inductance as a function of plunger position x
- From L(x), find force



Reluctance Model

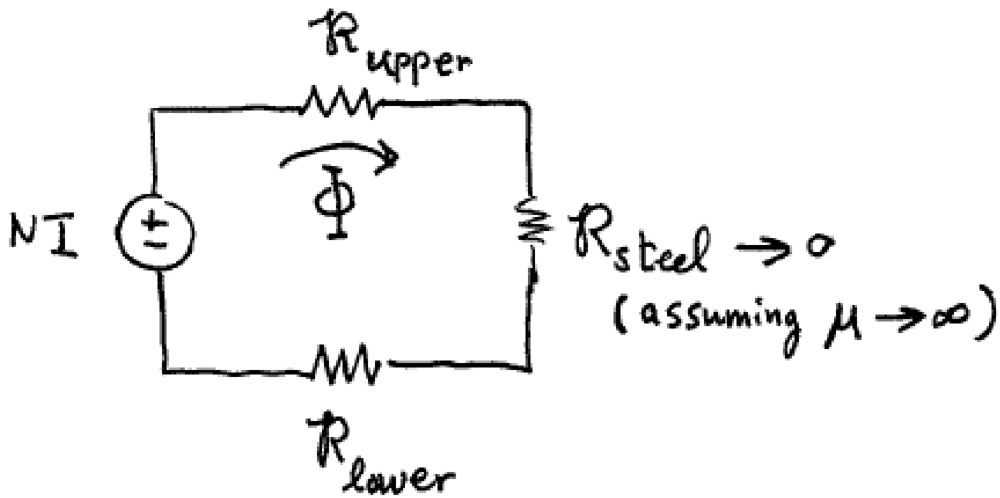
- Reluctance of steel is very small if the steel doesn't saturate

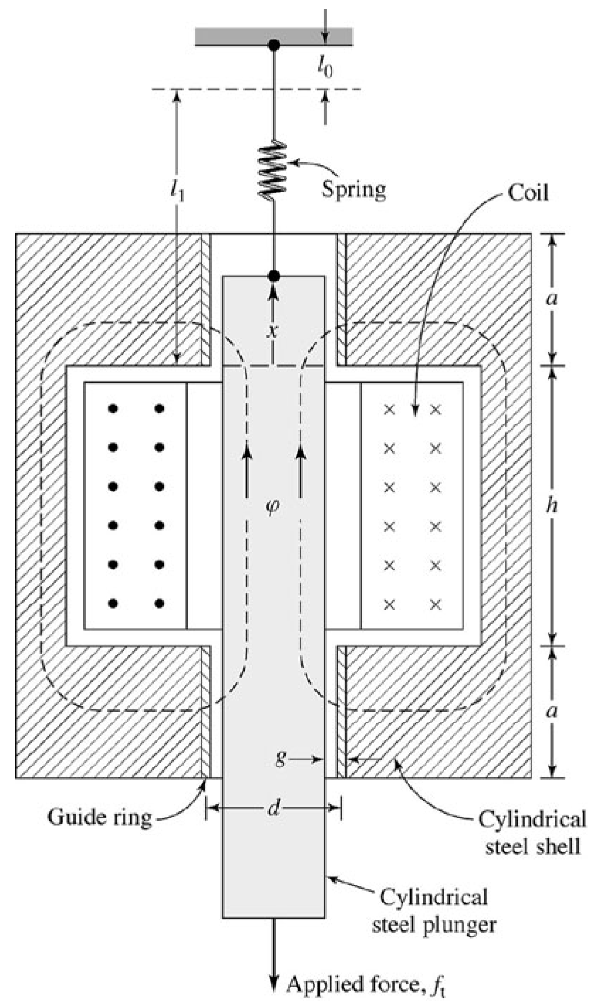




$$\Re = \frac{\text{Path length in direction of field}}{\mu(\text{Area of flux path perpendicular to field})}$$

Reluctance Model

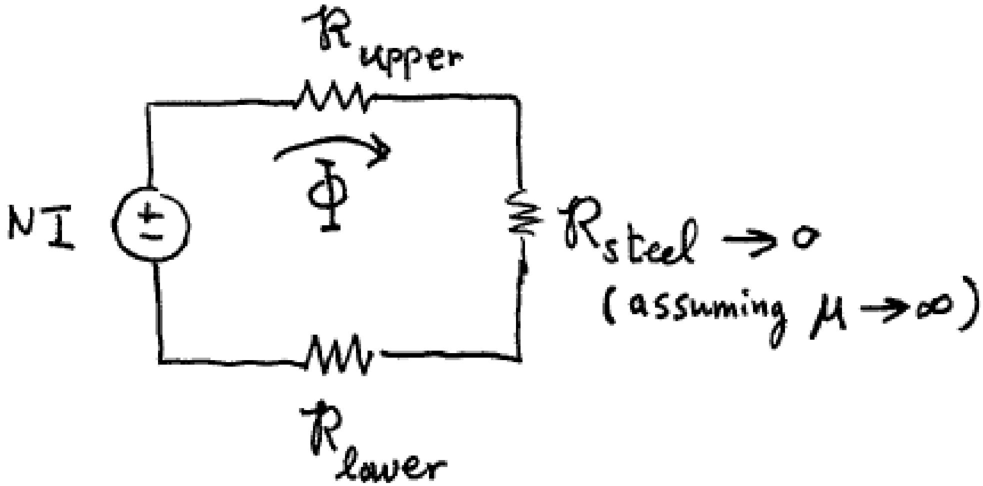




Upper gap: $\Re_{upper} = \dfrac{g}{\mu_o (\pi d) x}$

Lower gap: $\Re_{lower} = \dfrac{g}{\mu_o (\pi d) a}$

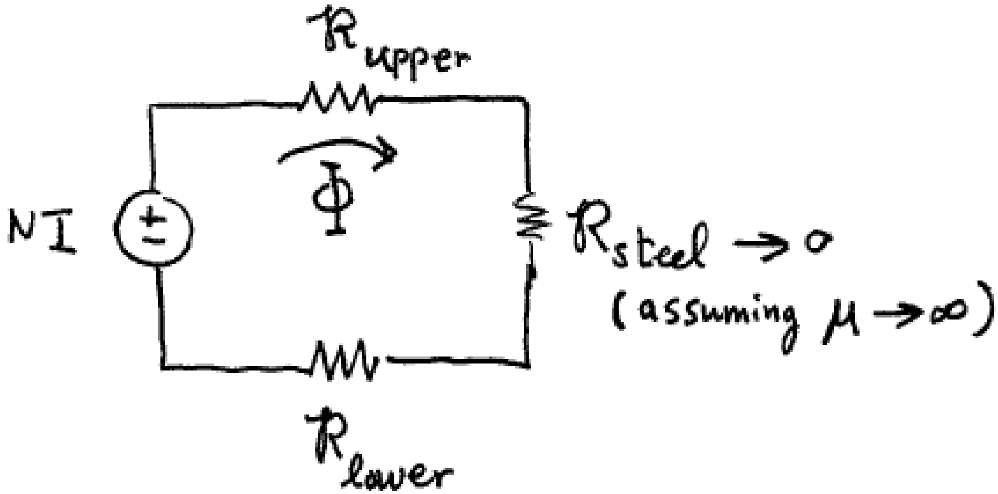
Flux



Flux:

$$\Phi = \frac{NI}{\Re_{upper} + \Re_{lower}}$$

Flux Linkage



Flux linkage:

$$\lambda = N\Phi = \frac{N^2 I}{\Re_{upper} + \Re_{lower}}$$

Inductance as a Function of Plunger Position

Inductance:

$$L = \frac{\lambda}{I} = \frac{N^2}{\Re_{upper} + \Re_{lower}}$$

$$\Re_{upper} + \Re_{lower} = \frac{g}{\mu_o \pi dx} + \frac{g}{\mu_o \pi da} = \left(\frac{g}{\mu_o \pi da} \right) \left(\frac{a+x}{x} \right)$$

$$L(x) = \left(\frac{\mu_o \pi da N^2}{g} \right) \left(\frac{x}{a+x} \right) = L_o \left(\frac{x}{a+x} \right)$$

Find Force

Once you know the inductance, finding the force is easy:

$$f_x = \frac{I^2}{2}\frac{dL(x)}{dx}$$

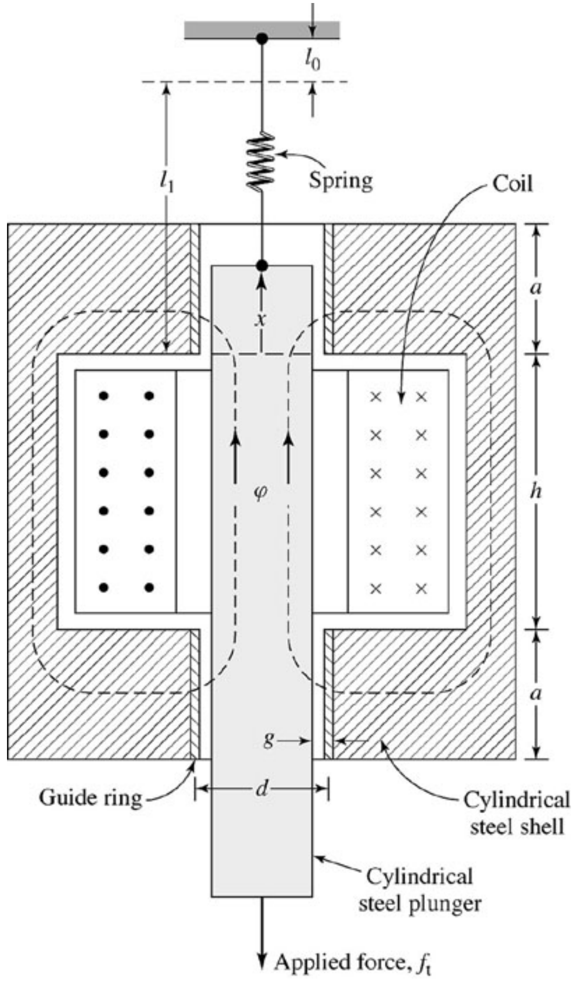
$$= \frac{I^2}{2} L_o \frac{d}{dx}\left(\frac{x}{a+x}\right)$$

$$= \frac{I^2}{2} L_o \frac{a}{(a+x)^2}$$

Solenoid Design Example

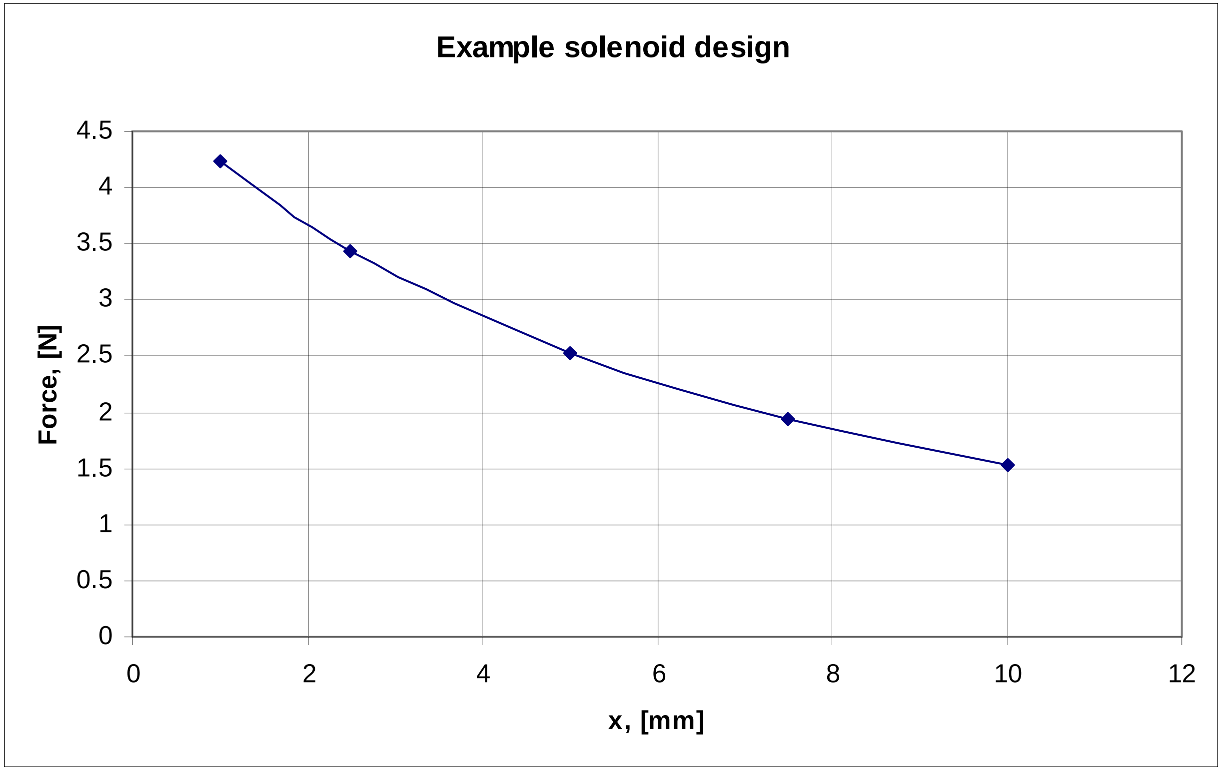
Dimensions of solenoid design example

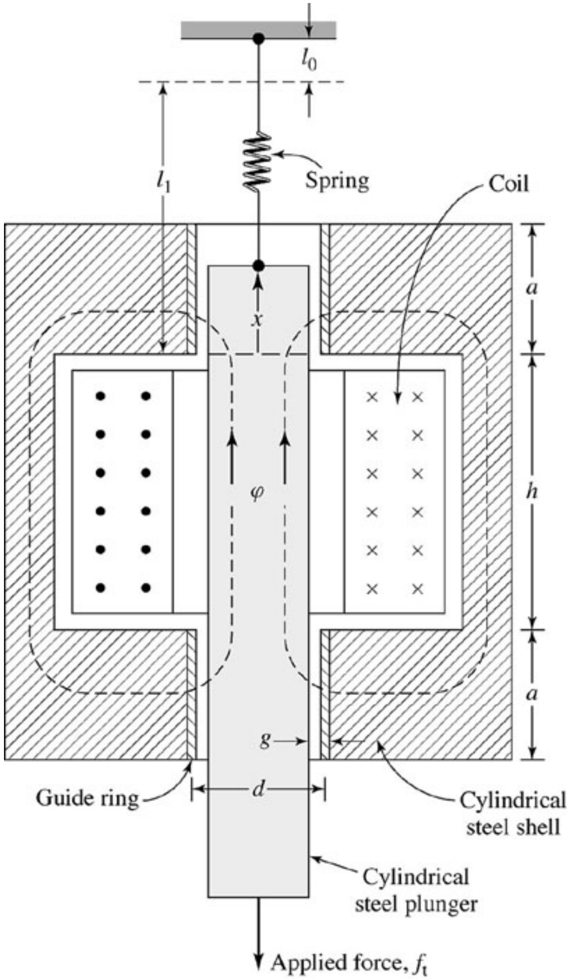
Item	Description	Dimension
a	Height of solenoid backiron arm	12.5 mm
h	Height of solenoid center backiron arm	10 mm
d	Radius to backiron	10 mm
g	Airgap	0.5 mm
r_{coil}	Coil mean radius	7.75 mm
x	Variable offset of plunger top from top of coil	5 mm (variable)
$r_{plunger}$	Plunger radius	9.5 mm



Design Example --- Analytic Result

- For NI = 354 A-turns (DC)
- Coil power dissipation ~ 3.5 Watts

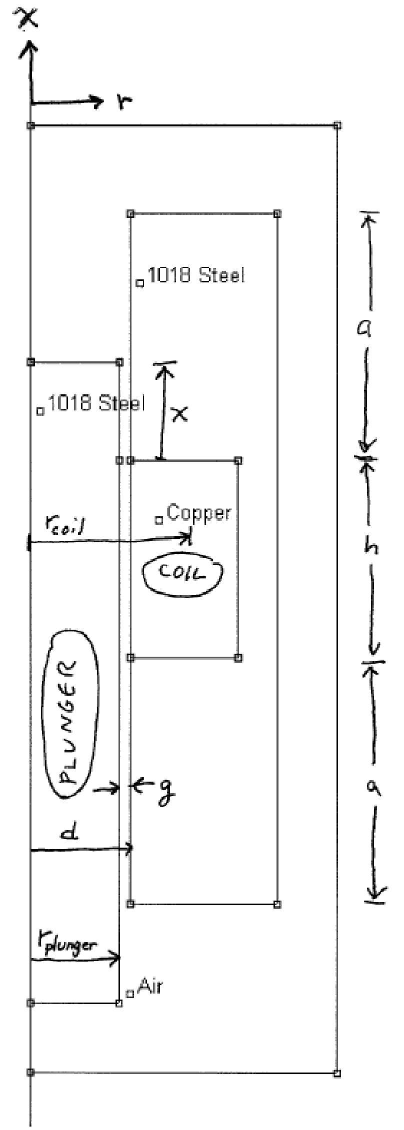




Simulation

- Trust, but verify
- 2D axisymmetric finite-element analysis program used
- Finite Element Method Magnetics (FEMM) by Dave Meeker at Foster-Miller

Simulation --- 2D Axisymmetric FEA



DIMENSIONS

$a = 12.5$ mm

$h = 10$ mm

$d = 10$mm

$g = 0.5$mm

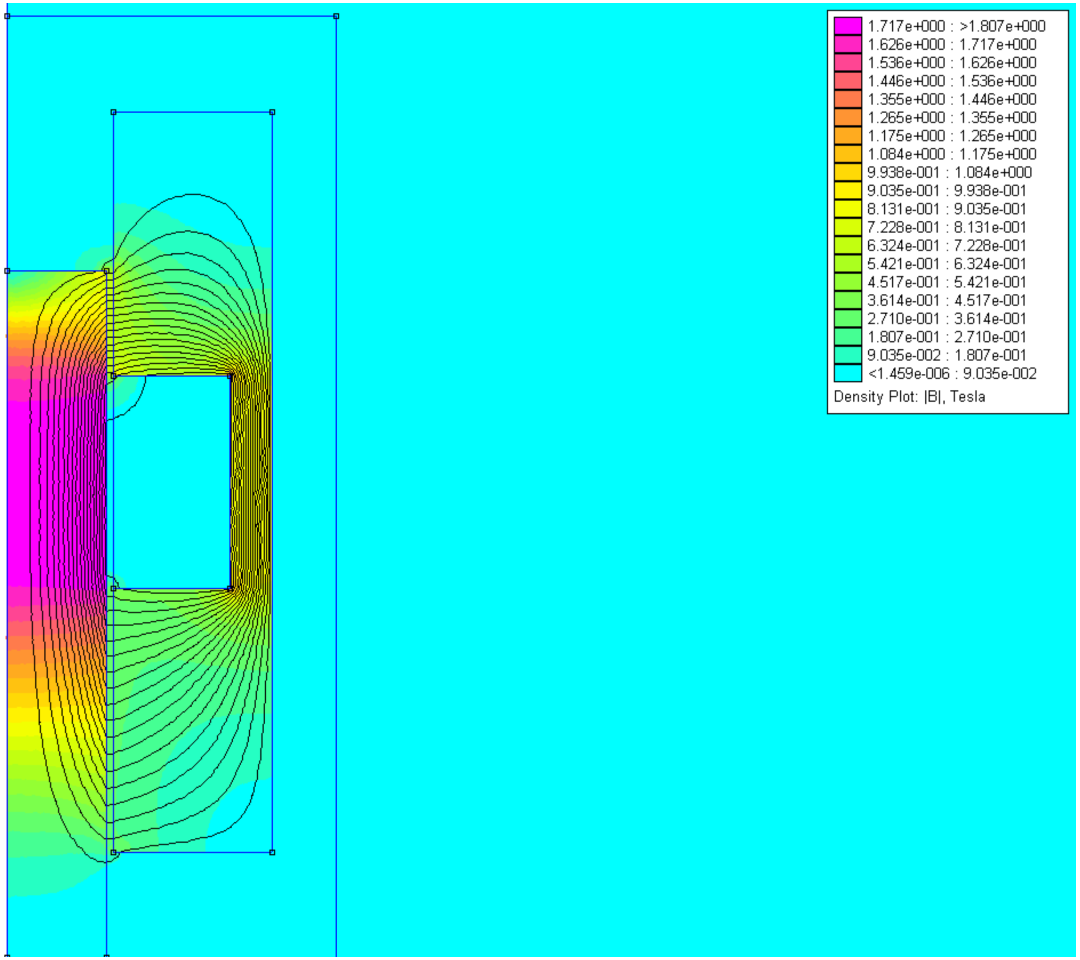
$r_{coil} = 7.75$mm

$x = 5$mm

$r_{plunger} = 4.5$ mm

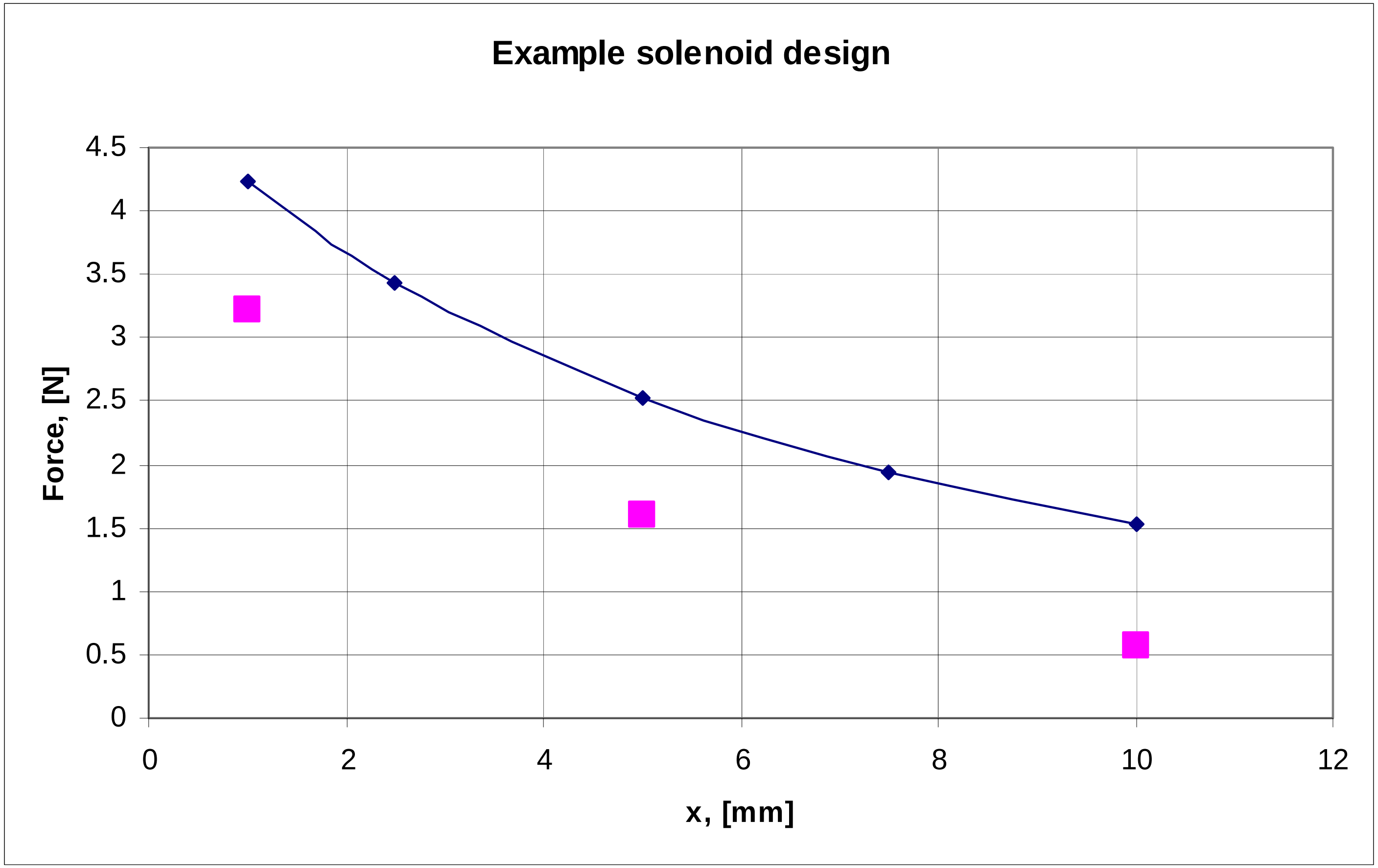
Simulation --- 2D Axisymmetric FEA

- Shown for x = 5 mm
- FEA shows f_x = 1.6 Newtons, P_{diss} = 3.5 Watts



Comparison of Analytic vs. FEA

- Note that FEA shows lower force than that predicted analytically
- Probably due to saturating iron reducing B and hence force



Introduction to Rotating Machines

- Elementary concepts and terminology
- AC machines overview
- DC machines overview
- MMF of distributed windings
- Magnetic fields in rotating machines
- Generated voltage
- Torque
- Linear machines

Motor Terminology

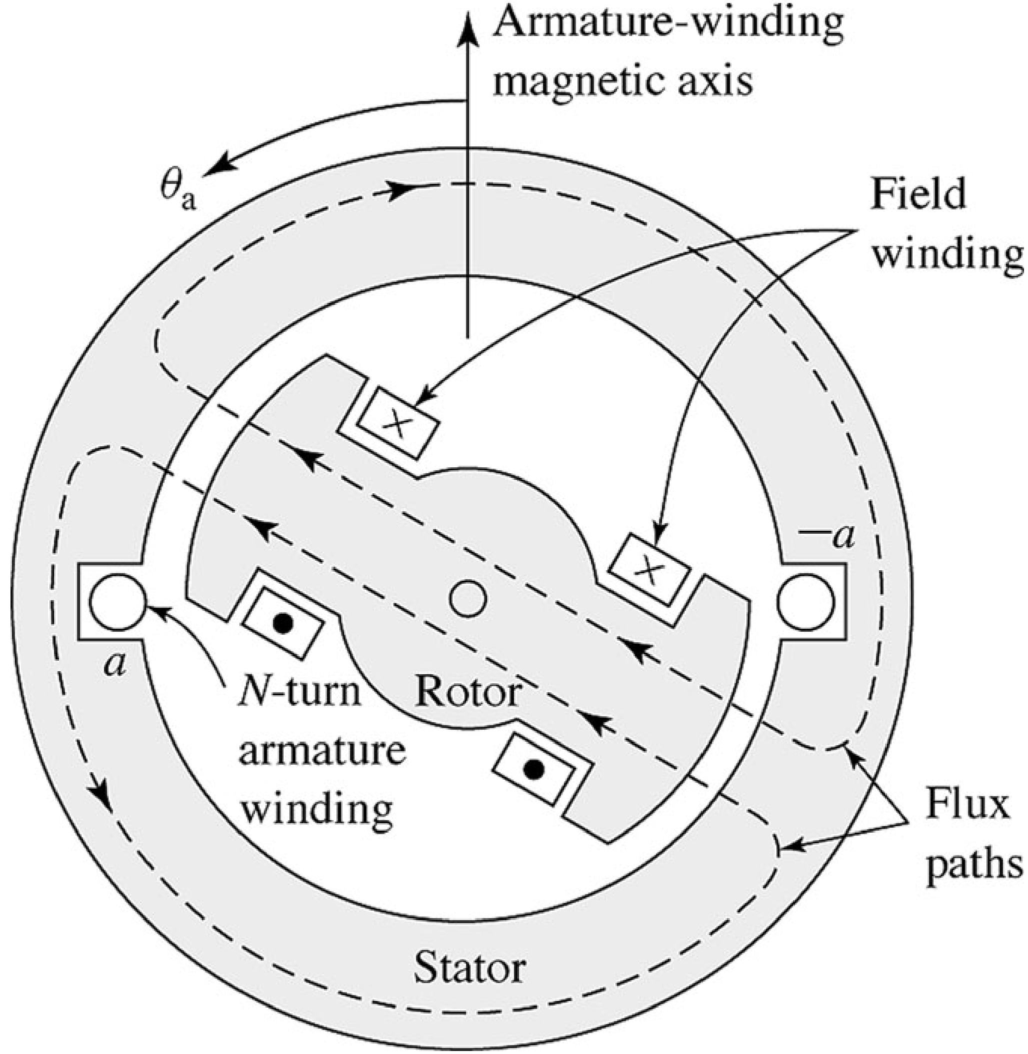
- *Armature winding* --- windings that carry AC currents
- *Stator* --- stationary part of the motor
- *Rotor* --- rotating part of the motor
- *DC machine* --- armature winding found on the rotor
- *AC machine* --- armature winding typically on the stator
- *Field winding* --- windings that carry DC current and produce main operating flux

Types of Machines

- AC machines
    - Synchronous motor
    - Induction motor
- DC machines

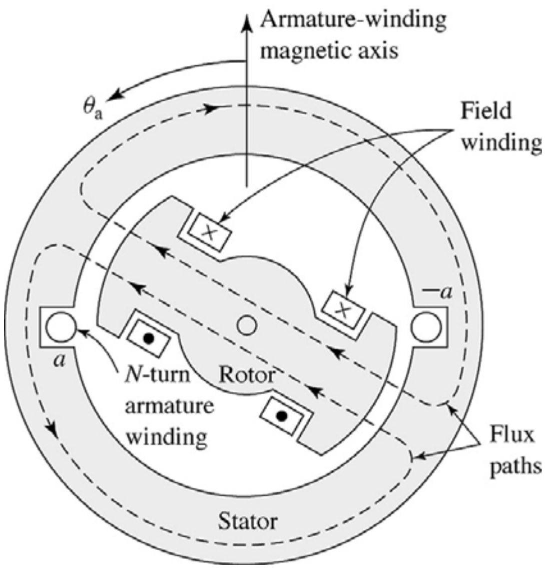
Simple 2-Pole Synchronous Generator

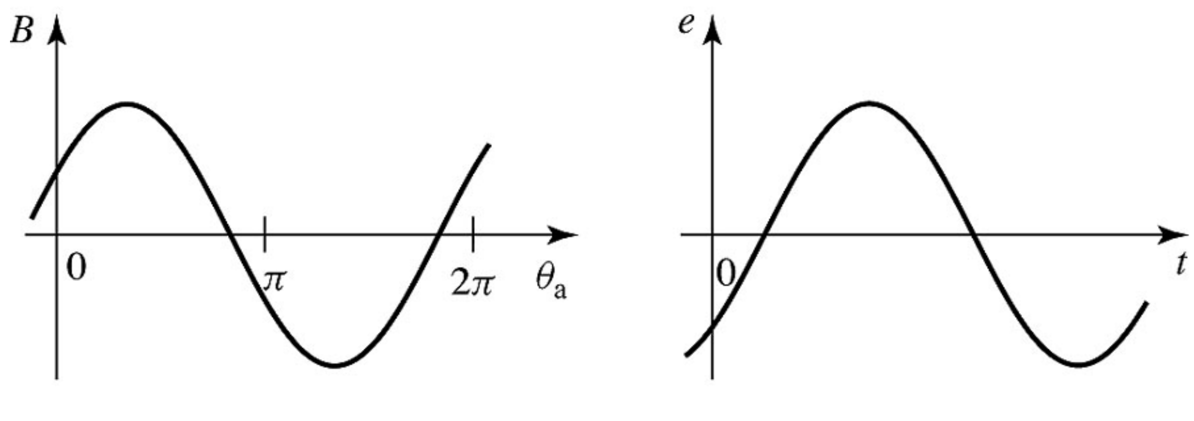
- This is a “salient pole” machine.
- Field winding excited by brushes contacting slip rings
- It advantageous to have the high power armature winding mounted to the stator for cooling purposes



Flux Density and Generated Voltage

- Idealized analysis assuming sinusoidal magnetic flux density in airgap varying with angle θ_a and flux produced by field winding only
- As the rotor rotates, there is a $d\lambda/dt$ which results in a sinusoidal armature voltage



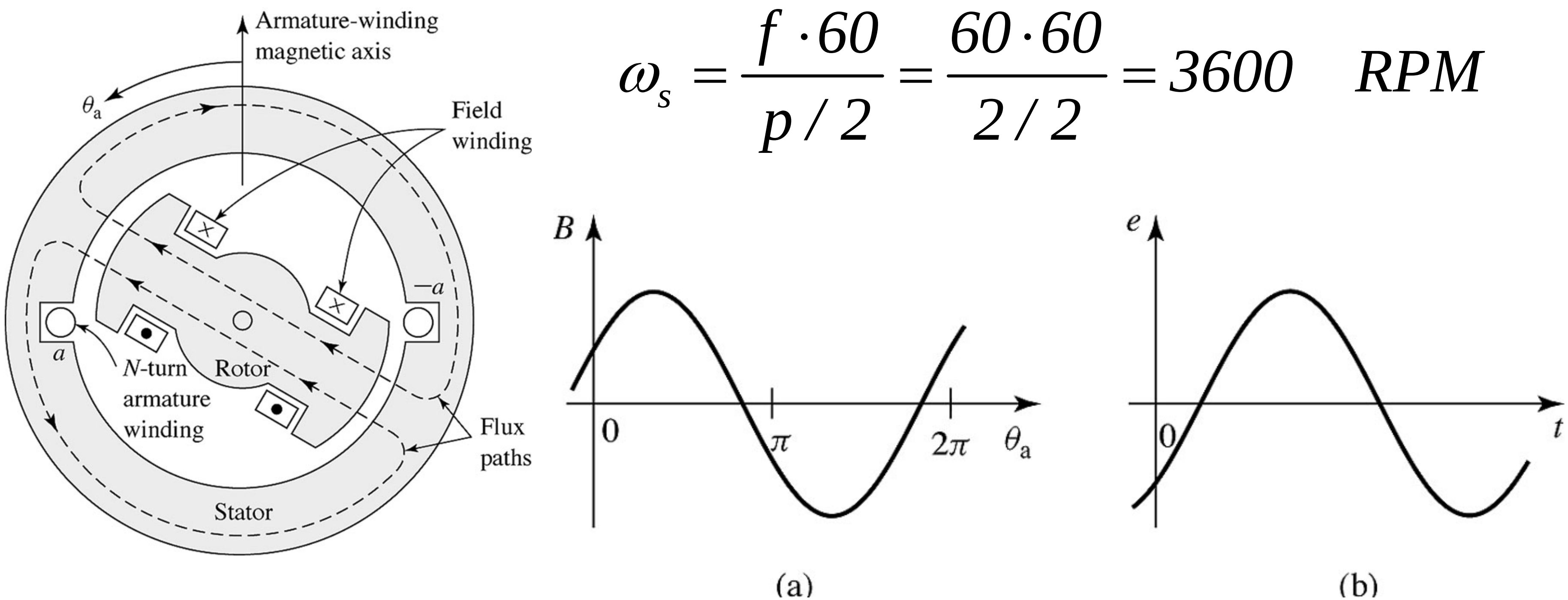


(a) (b)

Flux Density and Generated Voltage

- What is rotation speed needed to supply 60 Hz in a 2-pole machine?
- Frequency in Hz = rotation speed … hence “synchronous” generation occurs. 2-pole synchronous machine rotates at 3600 RPM to produce 60 Hz

$$\omega_s = \frac{f \cdot 60}{p/2} = \frac{60 \cdot 60}{2/2} = 3600 \quad RPM$$

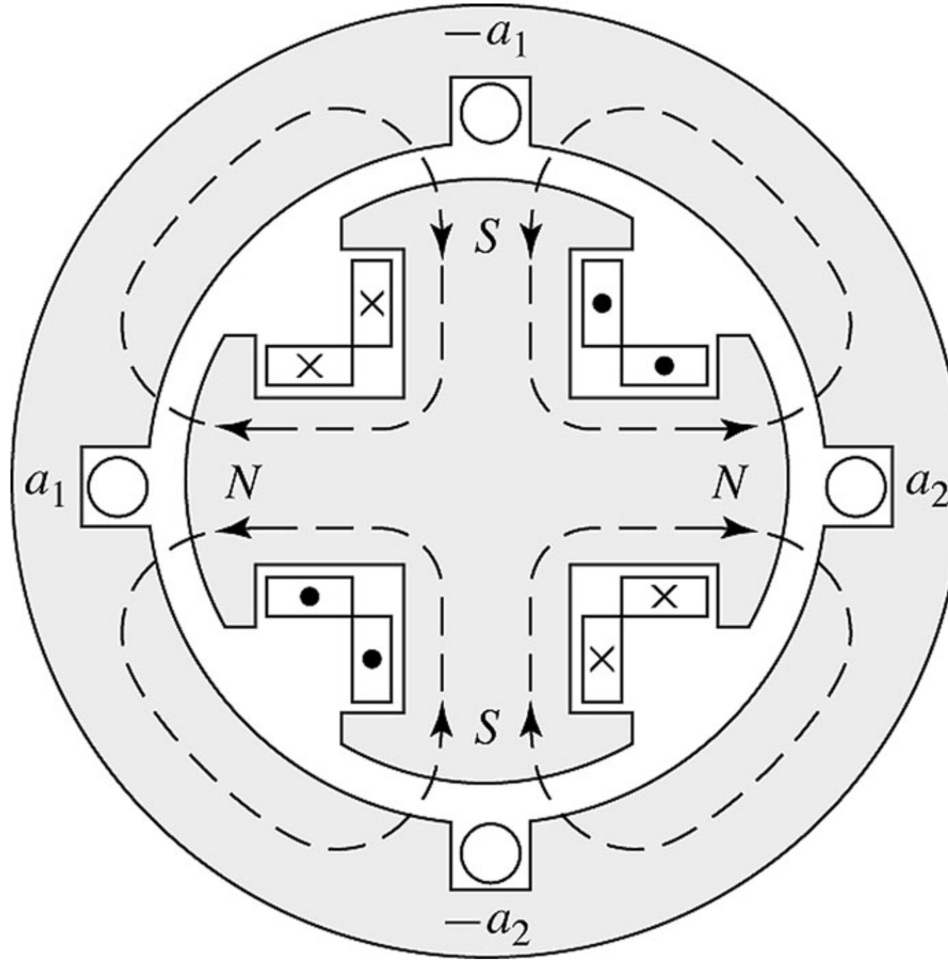


Four-Pole Single Phase Synchronous Generator

- This is also a “salient pole” machine
- Generated frequency is twice that of the two-pole machine
- 4-pole synchronous machine rotates at 1800 RPM to produce 60 Hz

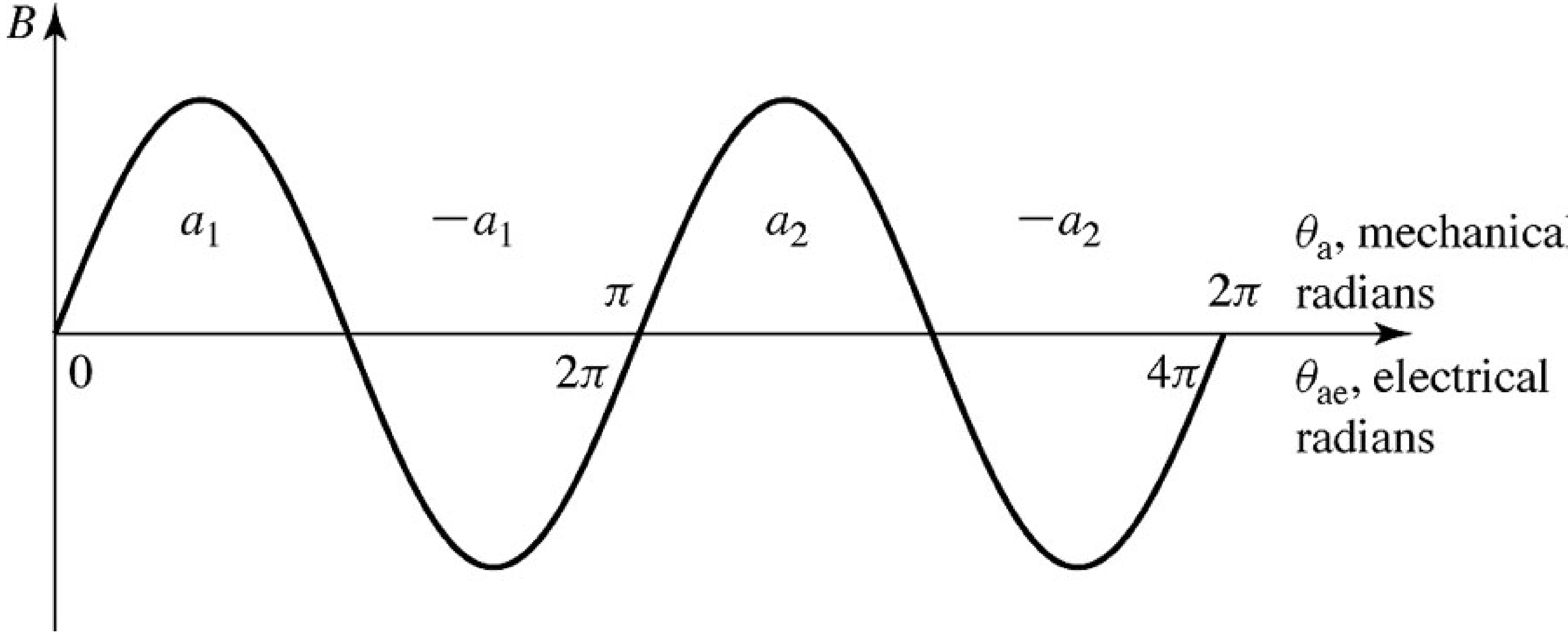
$$\theta_{ae} = \left(\frac{poles}{2}\right)\theta_a$$

θ_{ae} = electrical angle
θ_a = mechanical angle



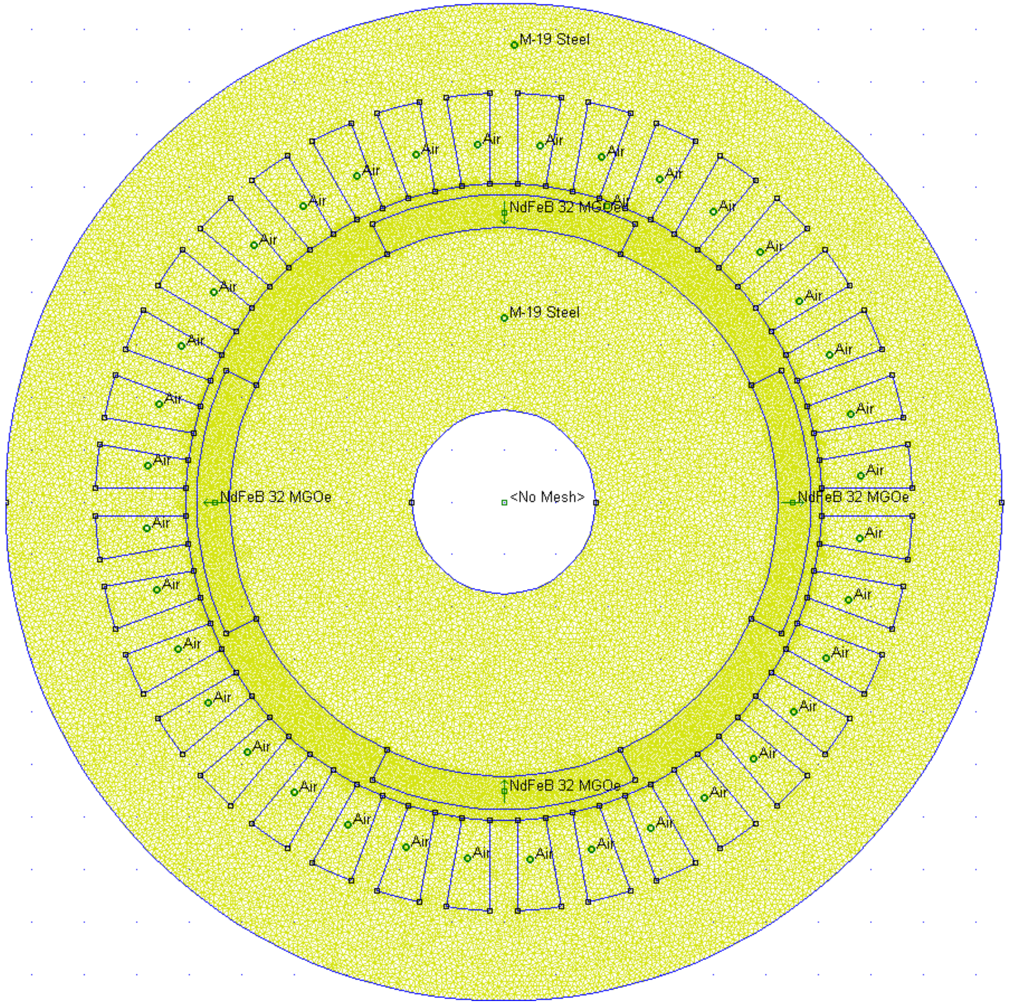
Distribution of Airgap Flux in 4-Pole Gen.

• Note that electrical angle is twice the mechanical angle, since there are 2 N-S electrical pole pairs per rotor rotation



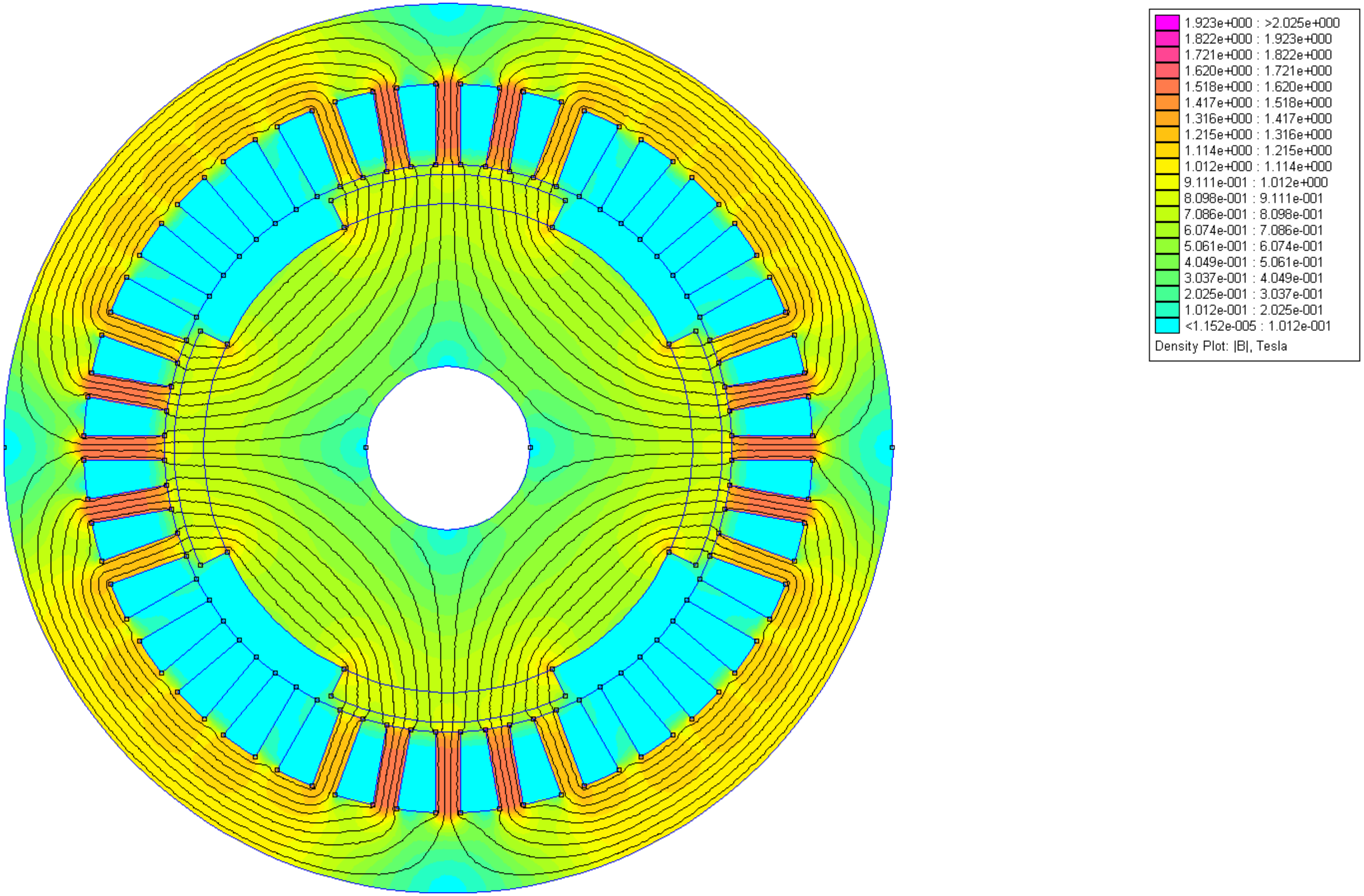
PM Machine

- 4 pole machine; field provided by NdFeB magnets



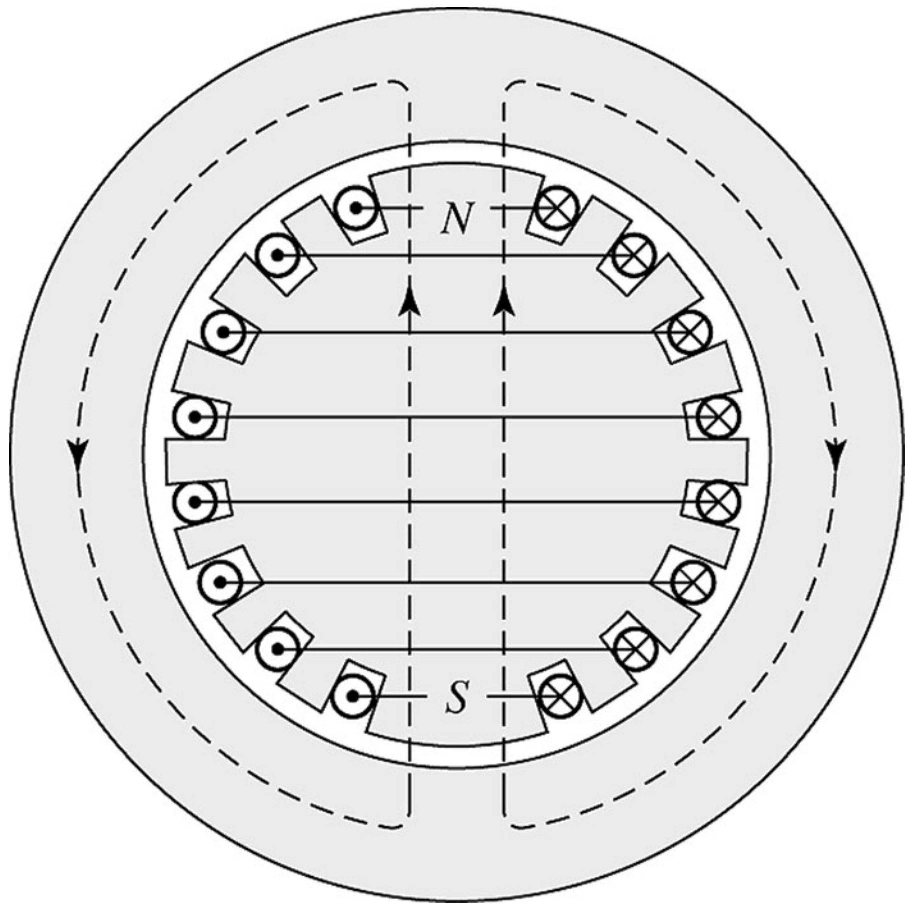
PM Machine

- 4 pole machine; field provided by NdFeB magnets



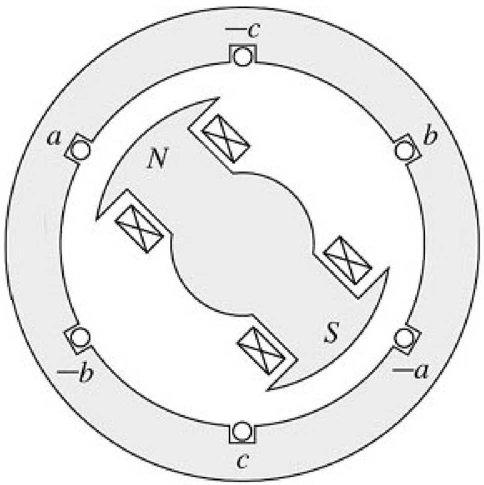
Nonsalient Pole Machine

- 2-poles; windings are distributed in slots in the rotor
- Suitable for high-speed generator



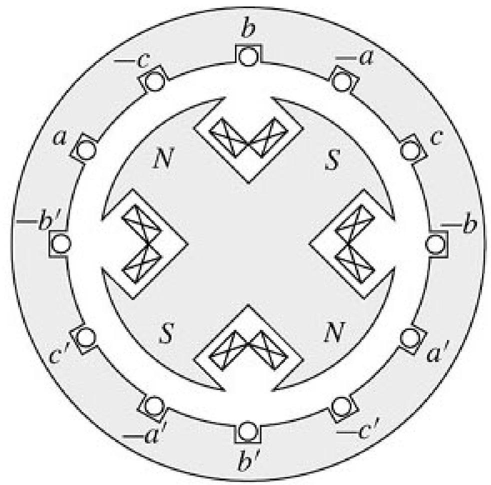
Three-Phase Generators

<u>2-pole</u>



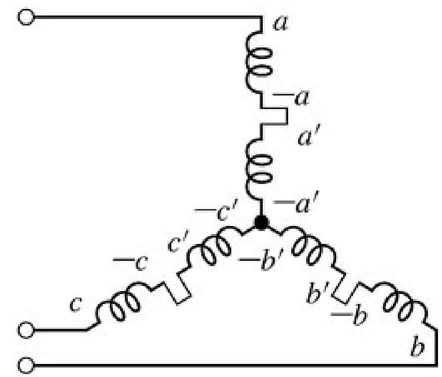
(a)

<u>4-pole</u>



(b)

<u>Y-connection of windings</u>



(c)

Induction Machines

- Stator winding is excited with AC currents, as in a synchronous machine
- AC flows in the rotor windings; rotor currents are produced by magnetic induction (i.e. transformer action) into short-circuited rotor windings
- We can think of an induction machine as a type of transformer where power is transformed between rotor and stator, with a change of frequency and flow of mechanical power
- Induction motor is the most common motor

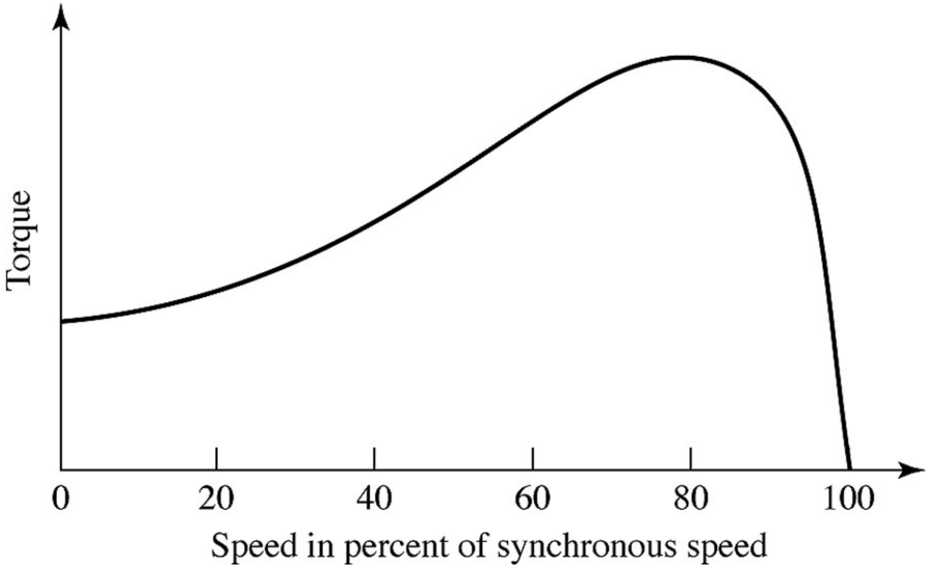
Typical Induction Motor Torque-Speed Curve

- The rotor of an induction machine does not rotate synchronously with the stator field; it "slips"

$$s = \frac{\omega_s - \omega_r}{\omega_s}$$

ω_s = synchronous speed
ω_r = rotor speed

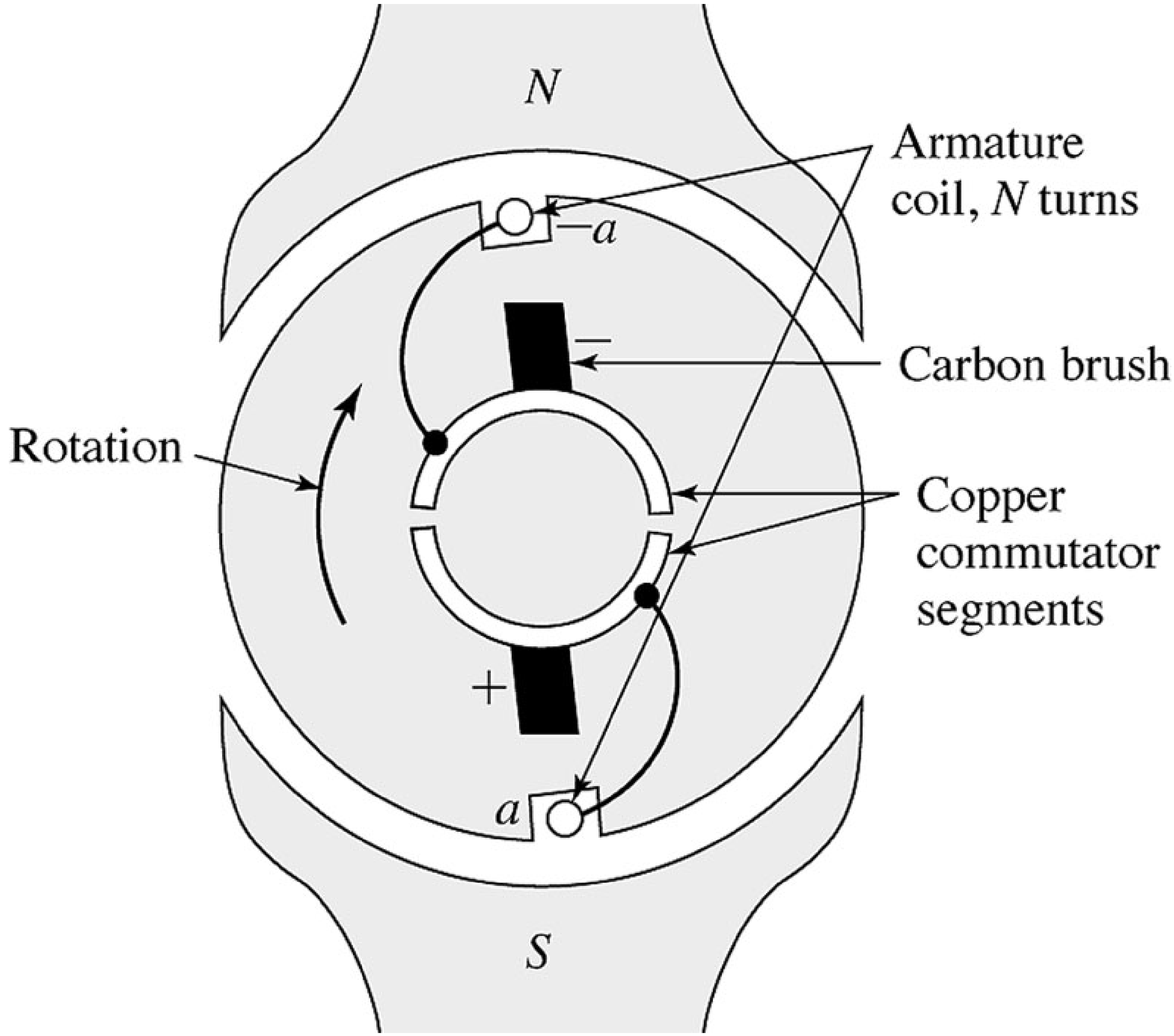
- Note that at full "synchronous speed" the motor generates zero torque



DC Machines

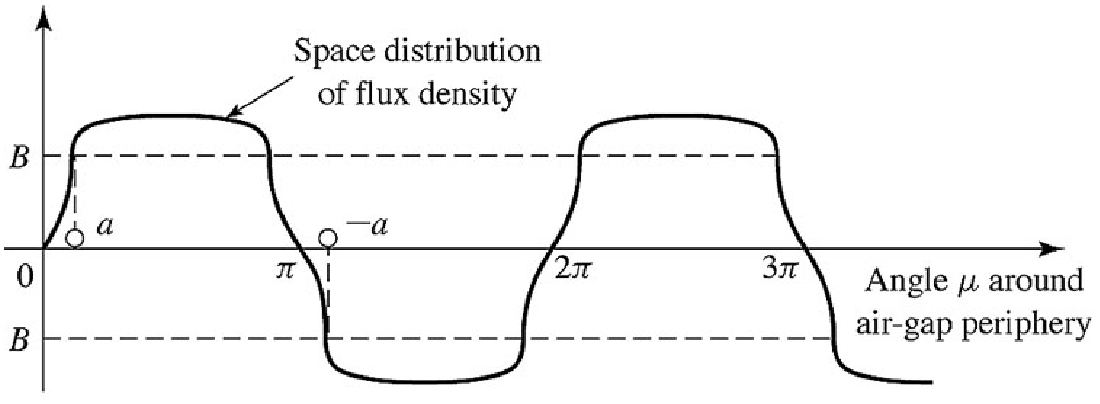
- Armature winding of a DC generator is on the rotor with current conducted from it by brushes
- Field winding is on the stator and is excited by DC current

Elementary DC Machine with Commutator

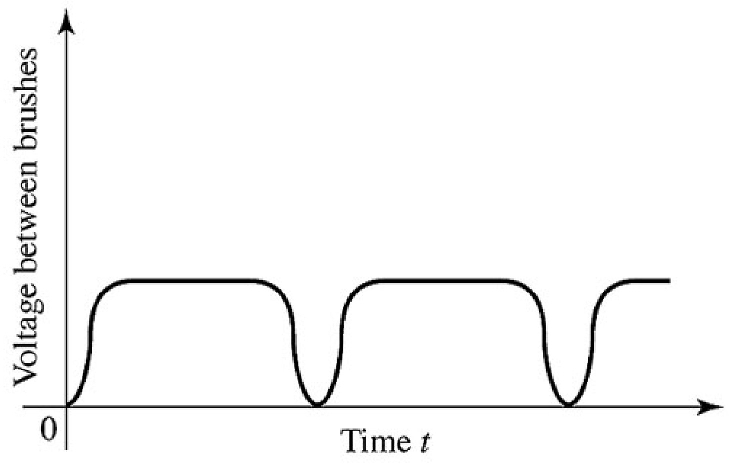


DC Machine Characteristics

- Brushes cause a rectification



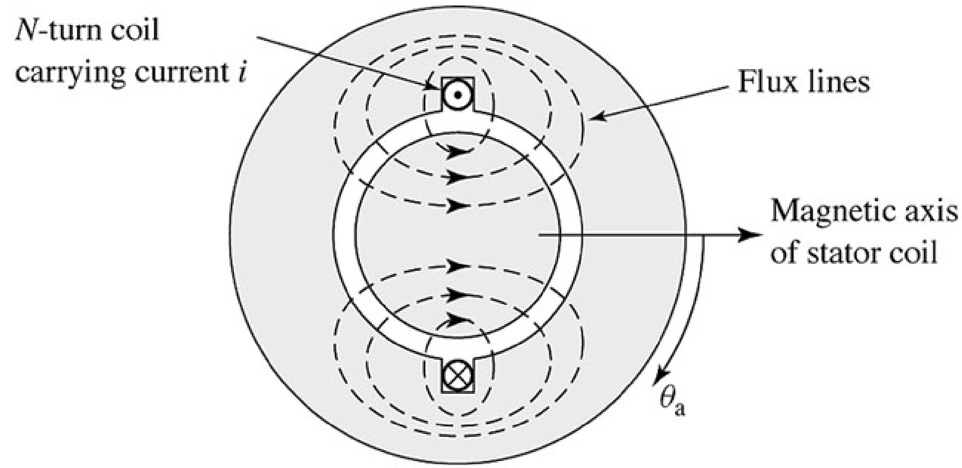
(a)



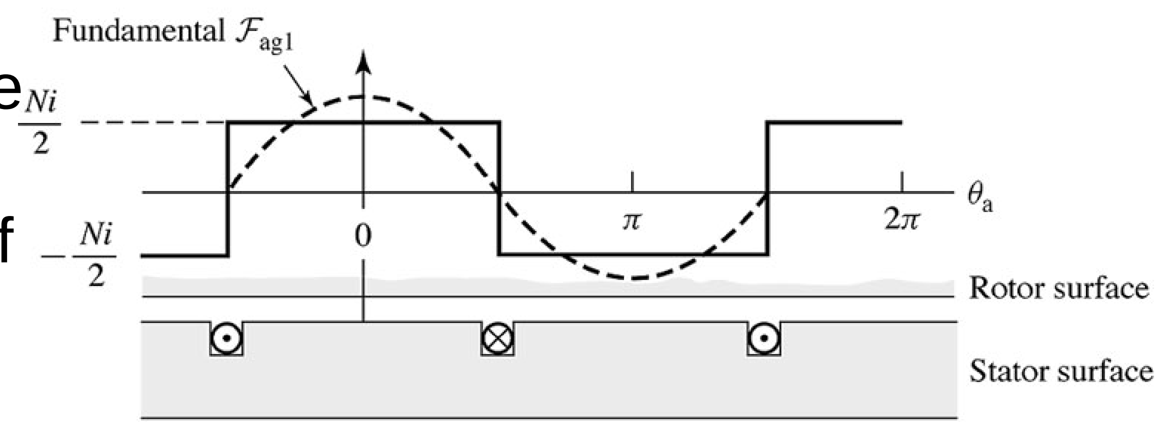
(b)

MMF of Concentrated Full-Pitch Winding

- This is an extreme example
- MMF is "magnetomotive force"
- Remember, by Ampere's law a current forces H to flow
- A current in a wire causes a change in the MMF
- Note first harmonic of airgap MMF (F_{ag1})

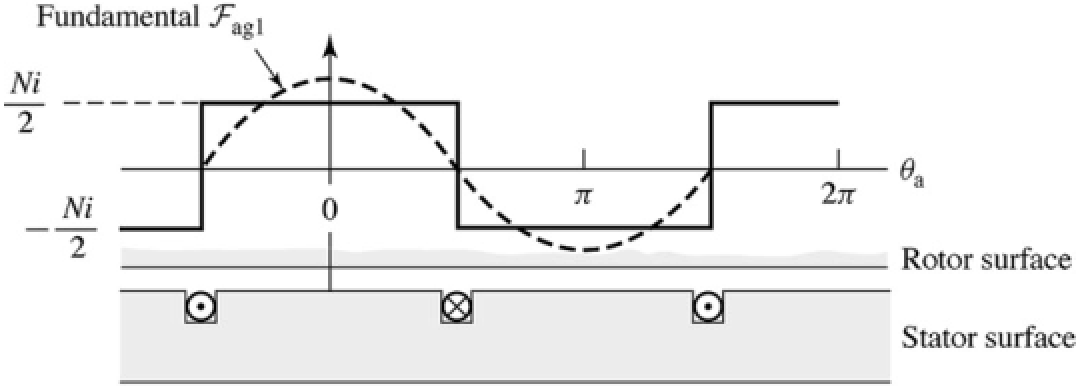


(a)



(b)

MMF of Concentrated Full-Pitch Winding



Fundamental component of airgap MMF

$$F_{ag1} = \left(\frac{4}{\pi}\right)\left(\frac{NI}{2}\right)\cos\theta_a$$

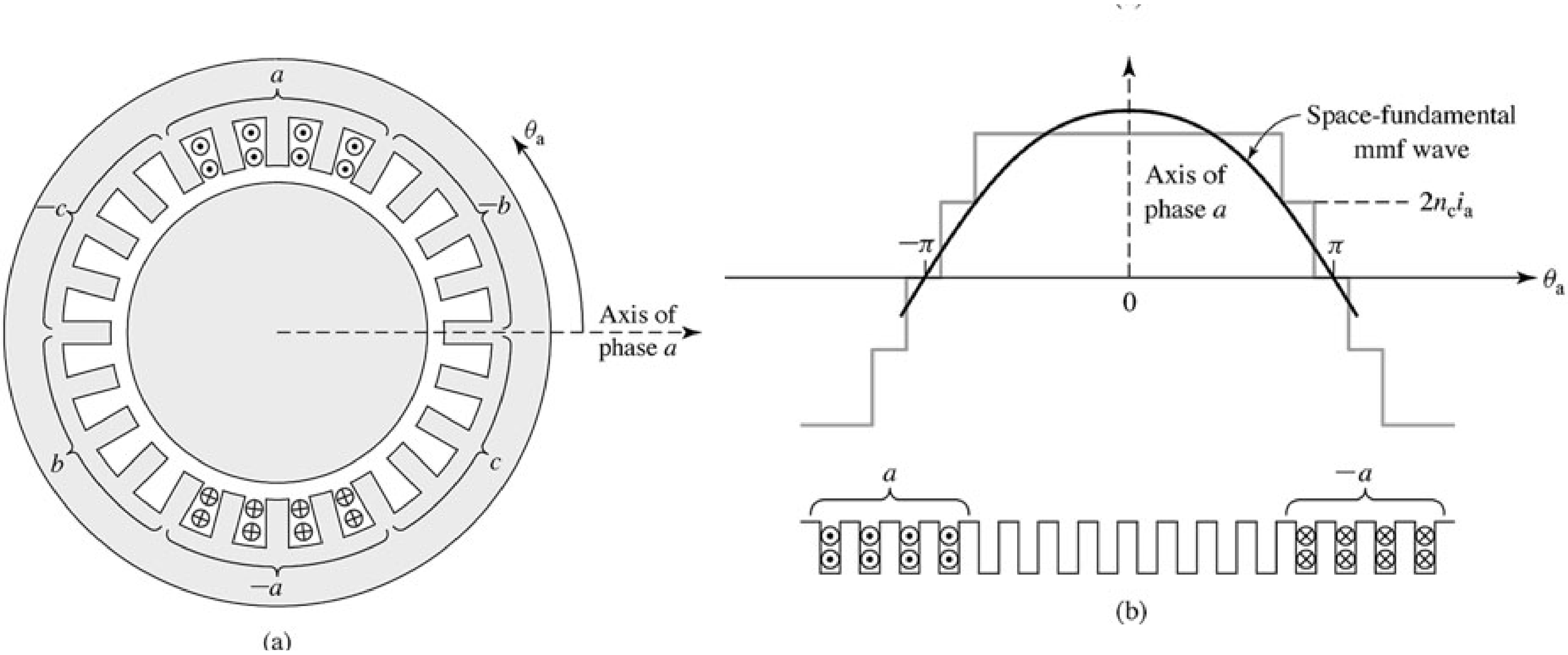
Peak value of airgap MMF

$$\left(F_{ag1}\right)_{peak} = \left(\frac{4}{\pi}\right)\left(\frac{NI}{2}\right)$$

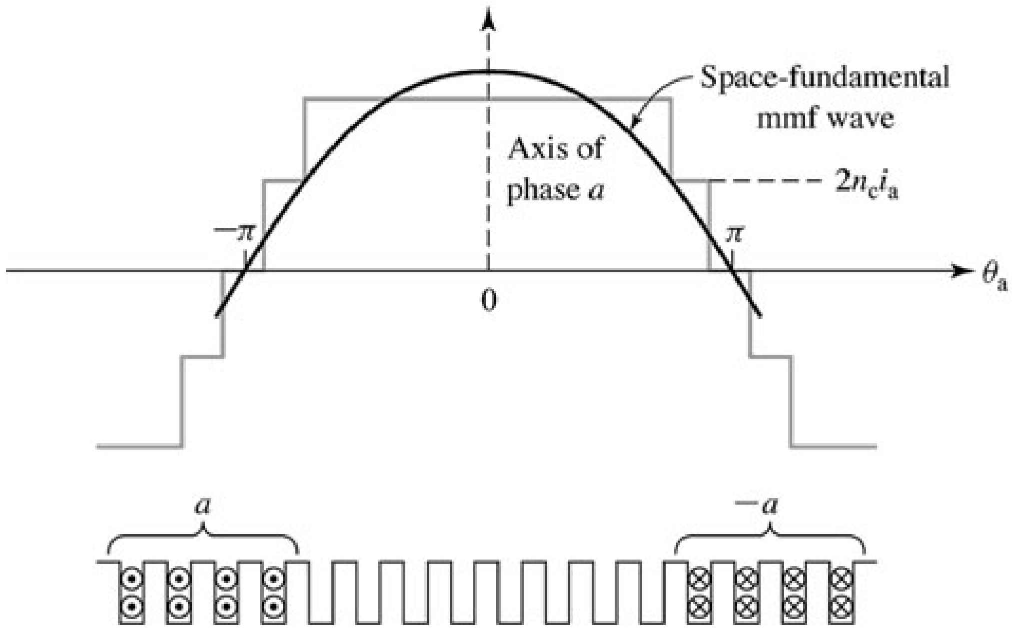
Distributed 2-Pole 3-Phase Winding

• We'd like to reduce harmonics in the MMF to reduce eddy losses, etc.

• A distributed winding better mimics a sinusoidal MMF



Distributed 2-Pole 3-Phase Winding



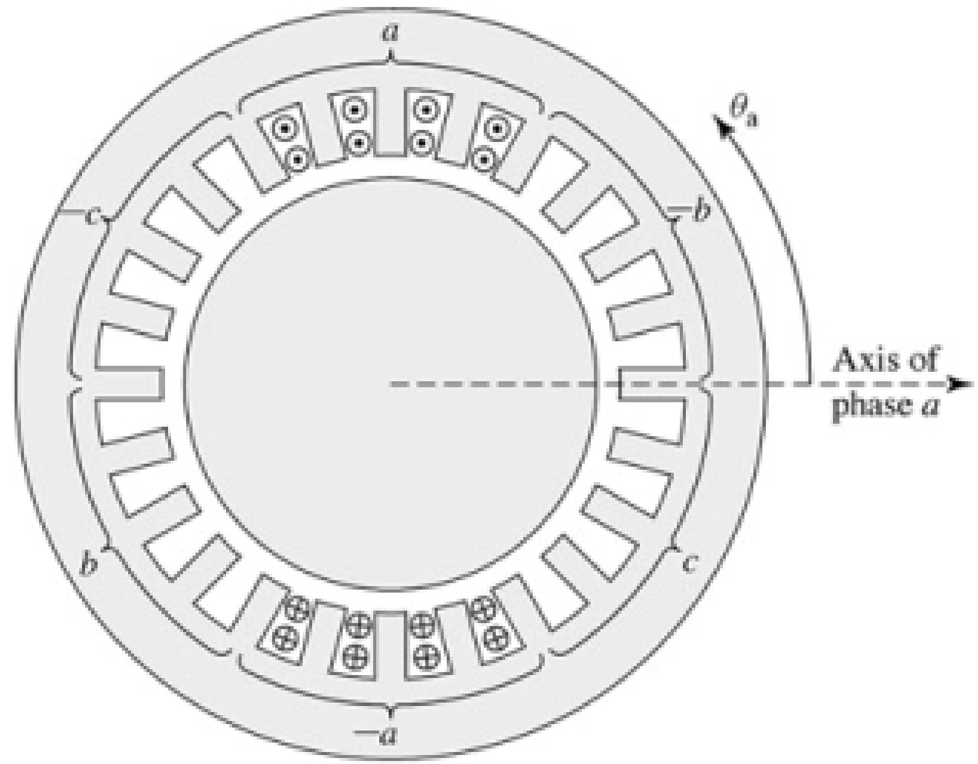
With N_{ph} series turns per phase:

$$F_{ag1} = \left(\frac{4}{\pi}\right)\left(\frac{k_w N_{ph}}{poles}\right) i_a \cos\left(\frac{poles}{2}\theta_a\right)$$

$k_w < 1$ is the winding factor

Example: Finding Winding Factor k_f

- *Fitzgerald*, Example 4.1
- Phase-a winding has 8 Nc-turn, full pitch coils
- Armature has 24 slots, 8 taken up by phase-a
- Each slot separated by $360^o/24 = 15^o$
- Assume that 4 slots containing phase a are at 67.5^o, 82.5^o, 97.5^o and 112.5^o with –a returns directly opposite
- Find winding factor k_f

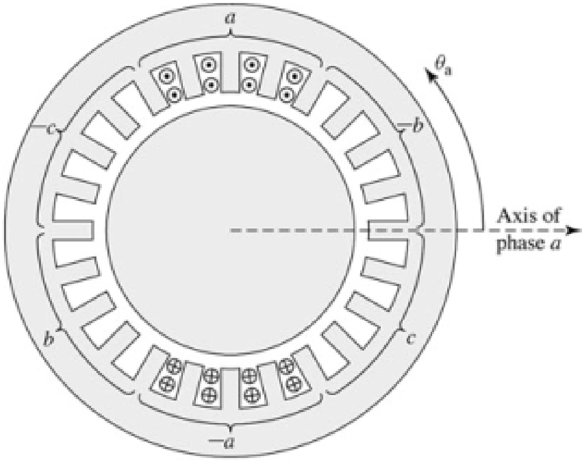


(a)

Example: Finding Winding Factor k_f

For coil at +112.5° and –67.5°

$$\left(F_{ag1}\right)_{22.5^o} = \left(\frac{4}{\pi}\right)\left(\frac{2N_c i_a}{2}\right)\cos\left(\theta_a - 22.5^o\right)$$



(a)

For coil at 67.5° and –112.5°

$$\left(F_{ag1}\right)_{-22.5^o} = \left(\frac{4}{\pi}\right)\left(\frac{2N_c i_a}{2}\right)\cos\left(\theta_a + 22.5^o\right)$$

We can add the contribution from the two other coils to get:

$$\left(F_{ag1}\right)_{total} = \left(F_{ag1}\right)_{-22.5^o} + \left(F_{ag1}\right)_{-7.5^o} + \left(F_{ag1}\right)_{7.5^o} + \left(F_{ag1}\right)_{22.5^o}$$

$$= \left(\frac{4}{\pi}\right)\left(\frac{2N_c}{2}\right)i_a\left[\cos\left(\theta_a + 22.5^o\right) + \cos\left(\theta_a + 7.5^o\right) + \cos\left(\theta_a - 7.5^o\right) + \cos\left(\theta_a - 22.5^o\right)\right]$$

Through a mathematical manipulation:

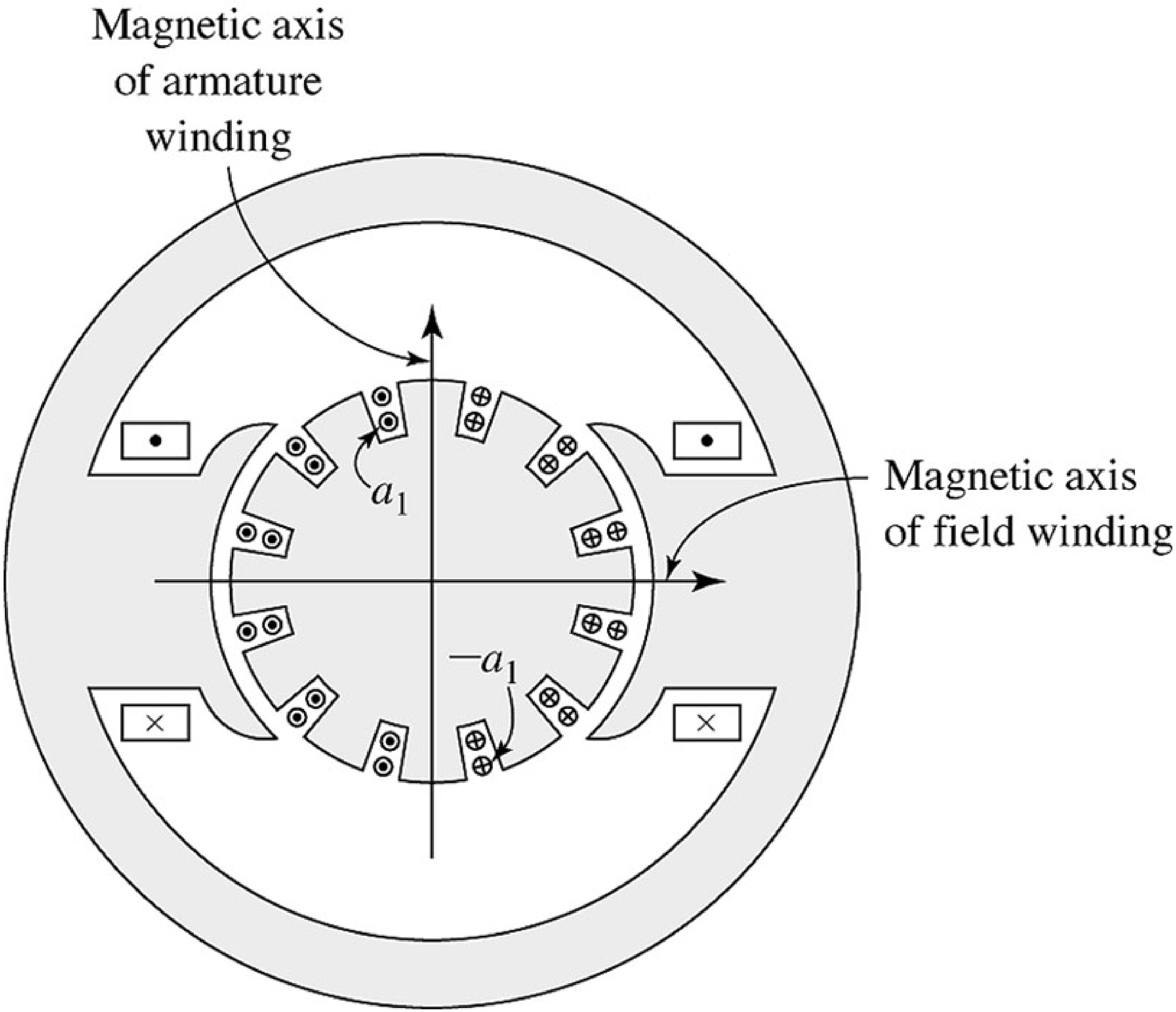
$$\cos(\alpha)\cos(\beta) = \frac{1}{2}\cos(\alpha - \beta) + \frac{1}{2}\cos(\alpha + \beta)$$

We can find:

$$\left(F_{ag1}\right)_{total} = \left(\frac{4}{\pi}\right)\left(\frac{7.66N_c}{2}\right)i_a\cos(\theta_a) = 4.88N_c i_a\cos(\theta_a)$$

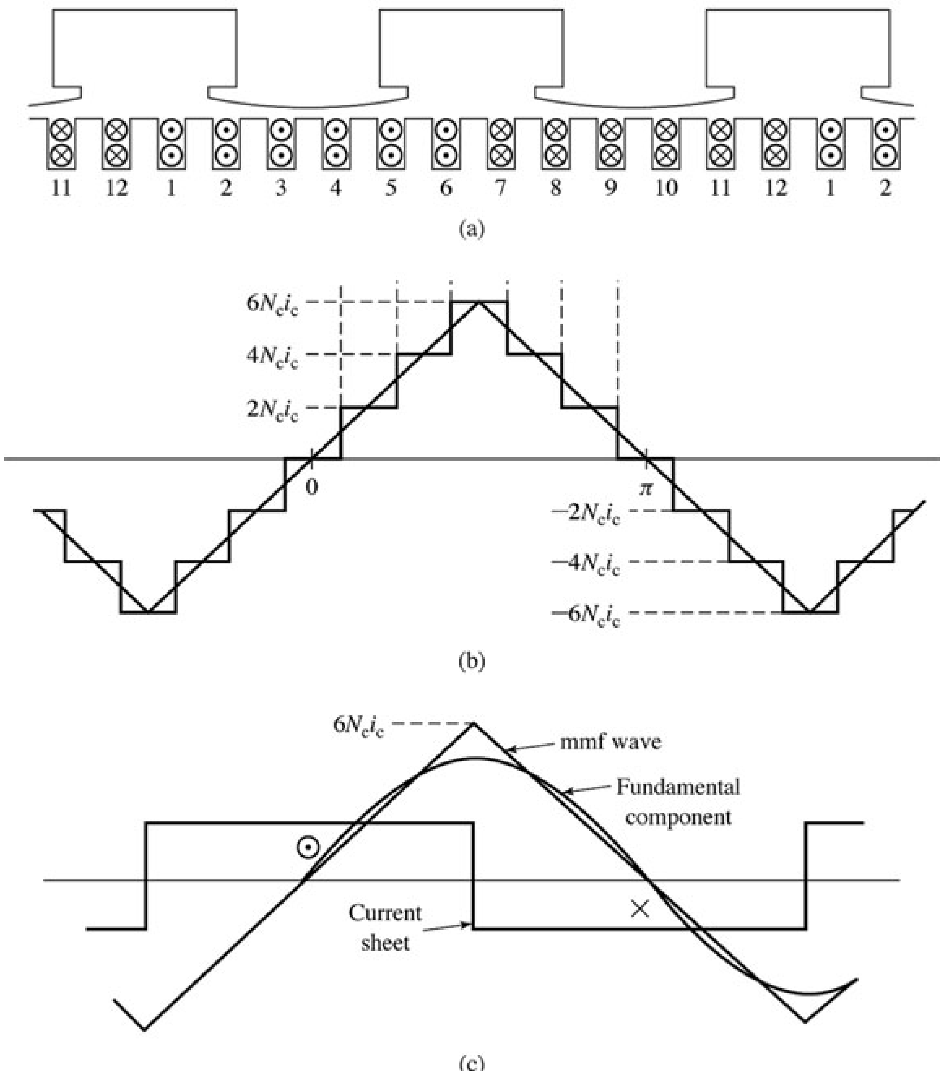
This means that the winding factor $k_w = 0.958$

Two-Pole DC Machine

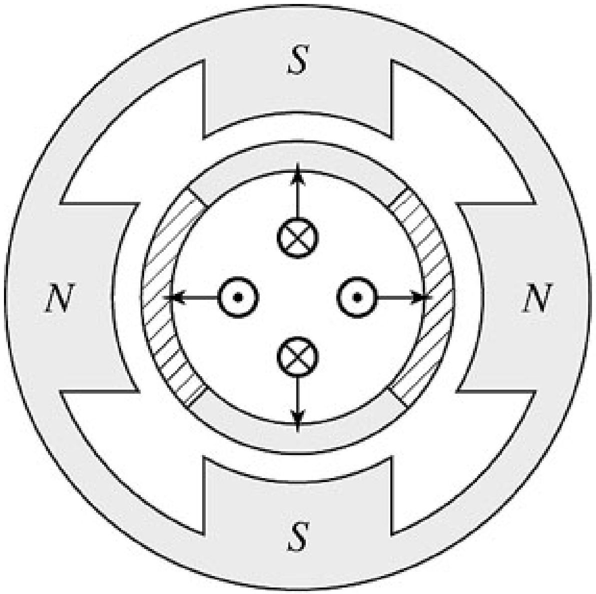


Developed Model of 2-Pole DC Machine

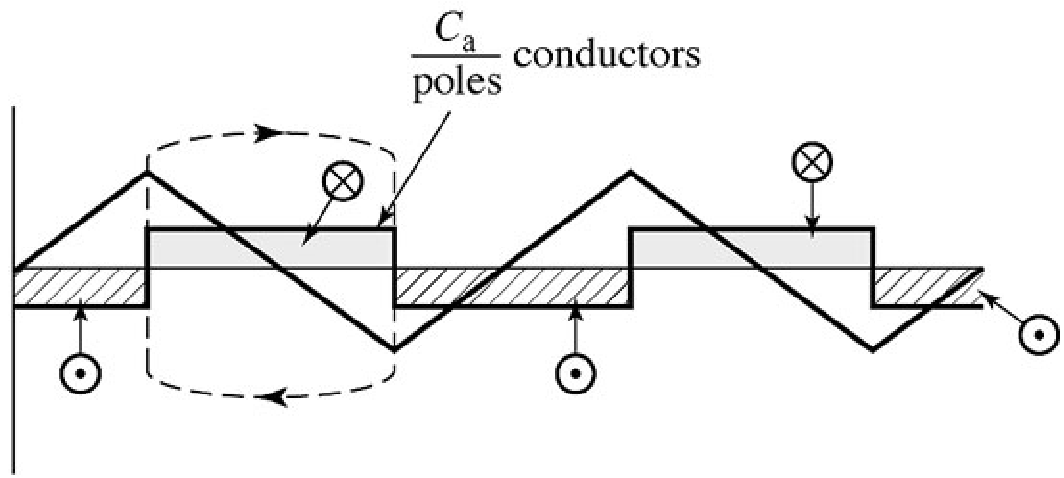
- Motor is cut open and laid-out flat



4-Pole DC Machine

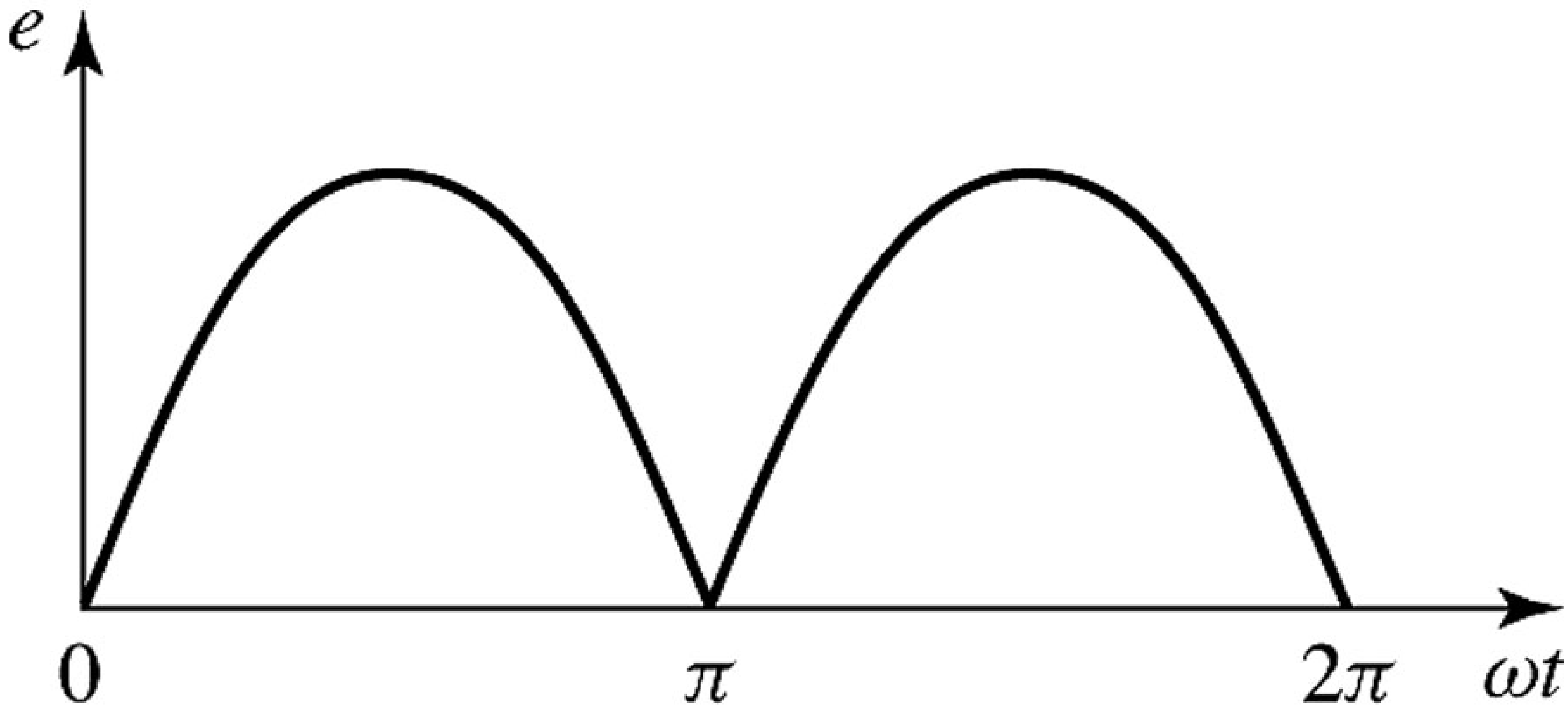


(a)



(b)

DC Machine --- Voltage Between Brushes



Airgap MMF and Field for Full-Pitch Winding

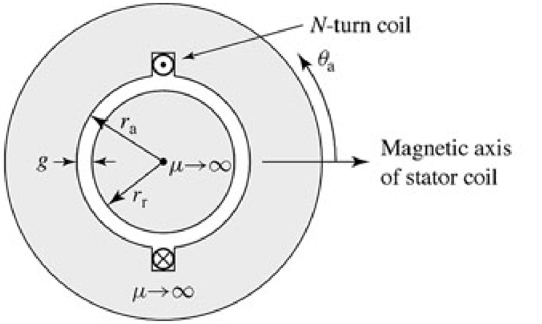
MMF is ampere-turns (NI)

If we know MMF, we can find the field H, since by Ampere's law:

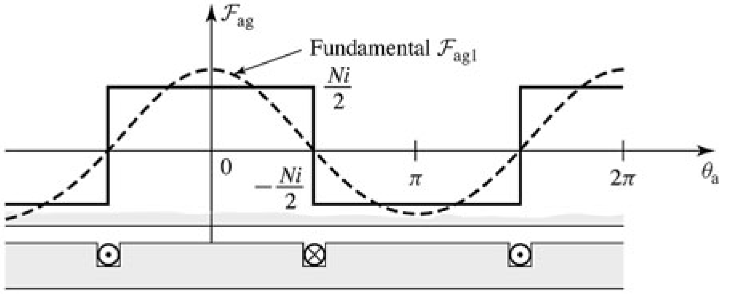
$$\oint \vec{H} \cdot d\vec{l} = NI$$

In a uniform gap machine, we can find H_{ag} by dividing F_{ag} by the airgap length

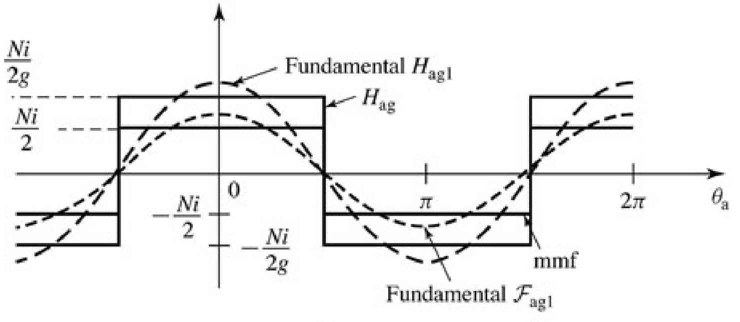
$$H_{ag} = \frac{F_{ag}}{g}$$



(a)



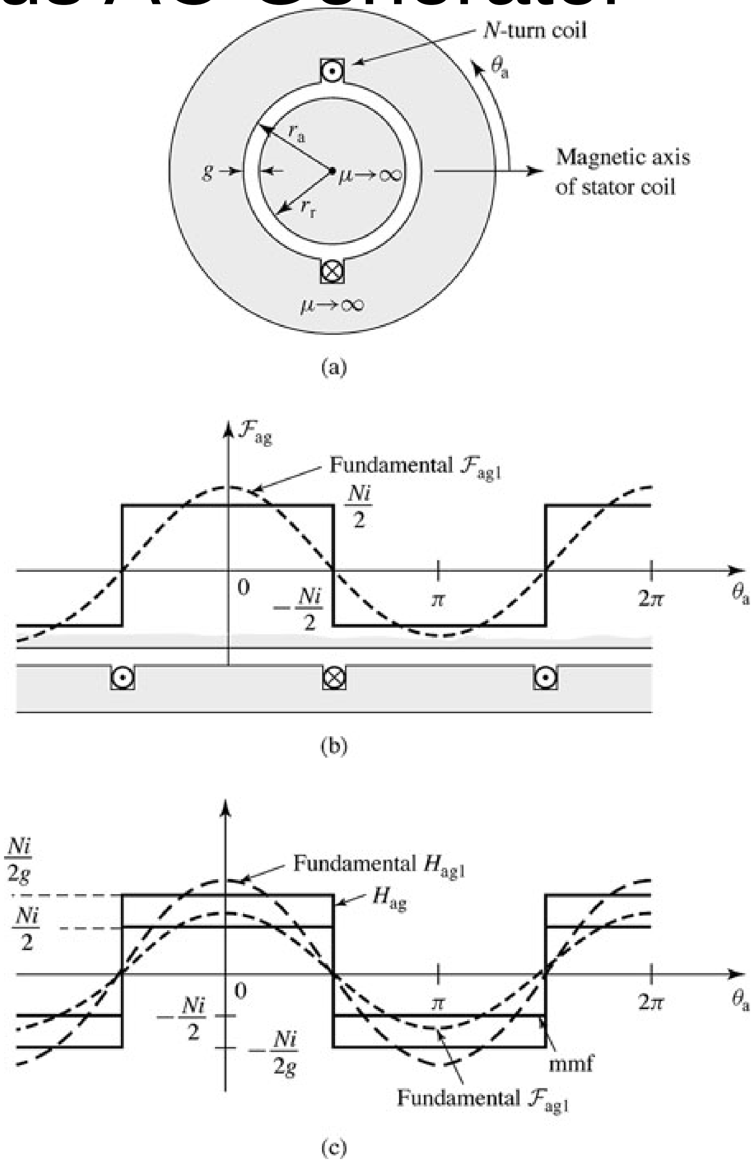
(b)



(c)

Example: Synchronous AC Generator

- *Fitzgerald*, Example 4.2
- A 4-pole synchronous AC generator has a smooth airgap and a distributed rotor winding with 263 series turns, a winding factor of 0.935 and an airgap length of 0.7 mm. Find rotor current required to produce a peak flux density of 1.6T in the airgap



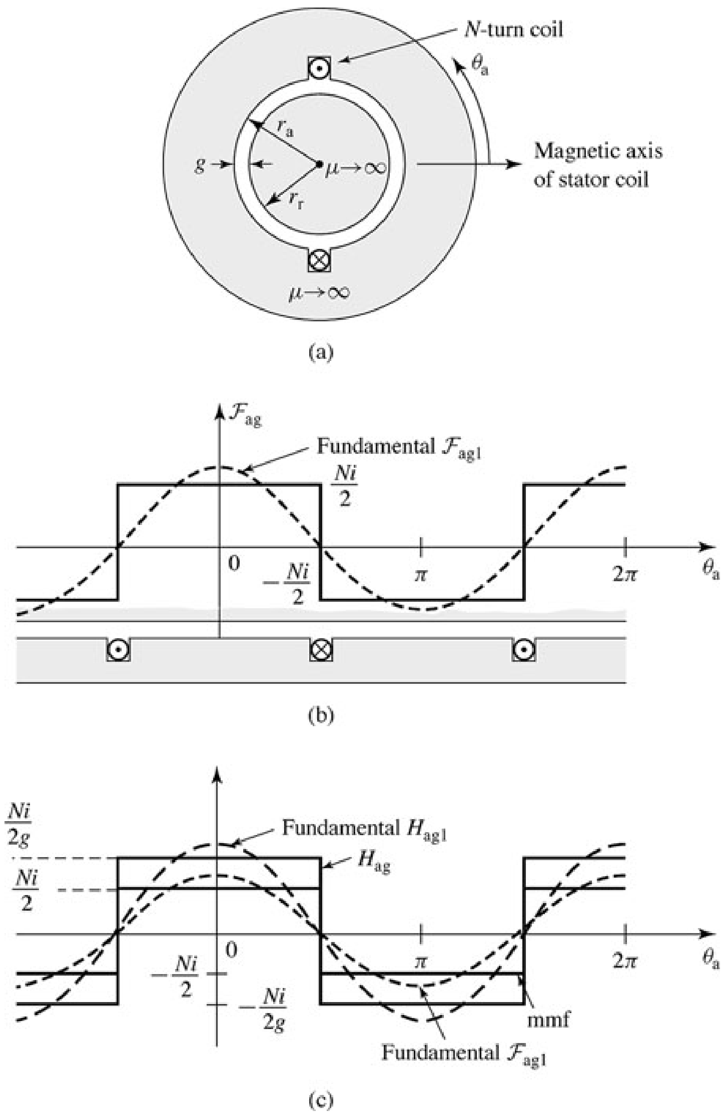
Example: Synchronous AC Generator

Strategy: Find H_{ag} and remember that $B_{ag} = \mu_o H_{ag}$

$$(B_{ag1})_{peak} = \frac{\mu_o (F_{ag1})_{peak}}{g} = \mu_o \left(\frac{4}{\pi}\right)\left(\frac{1}{g}\right)\left(\frac{k_r N_r}{poles}\right) I_r$$

$$\therefore I_r = \left(\frac{\pi g \times poles}{4\mu_o k_r N_r}\right)(B_{ag1})_{peak}$$

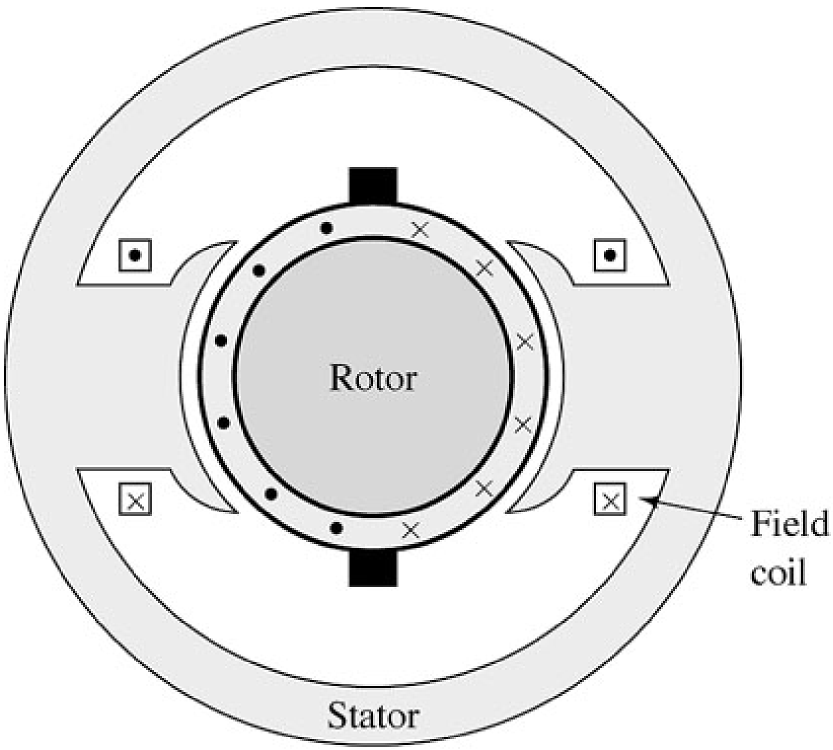
$$= \left(\frac{\pi \times 0.0007 \times poles}{4(4\pi \times 10^{-7})(0.935)(263)}\right)(1.6) = 11.4A$$



Salient-Pole Machines

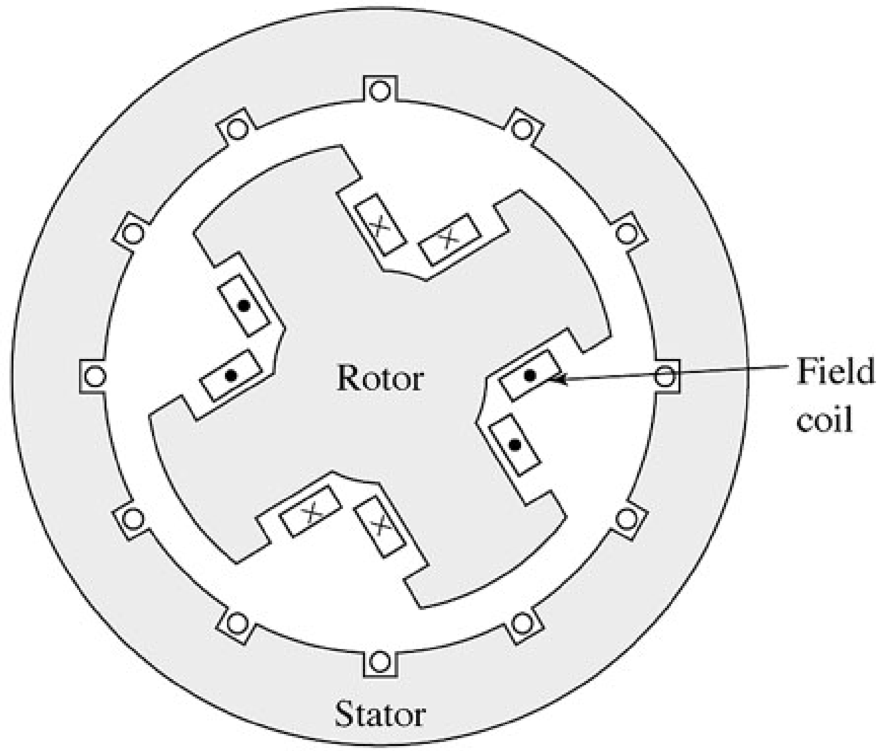
- Non-uniform airgap; airgap magnetic field distribution is more complex than a uniform gap machine
- Can be solved by FEA or the use of simplifying assumptions

- Salient pole DC machine



(a)

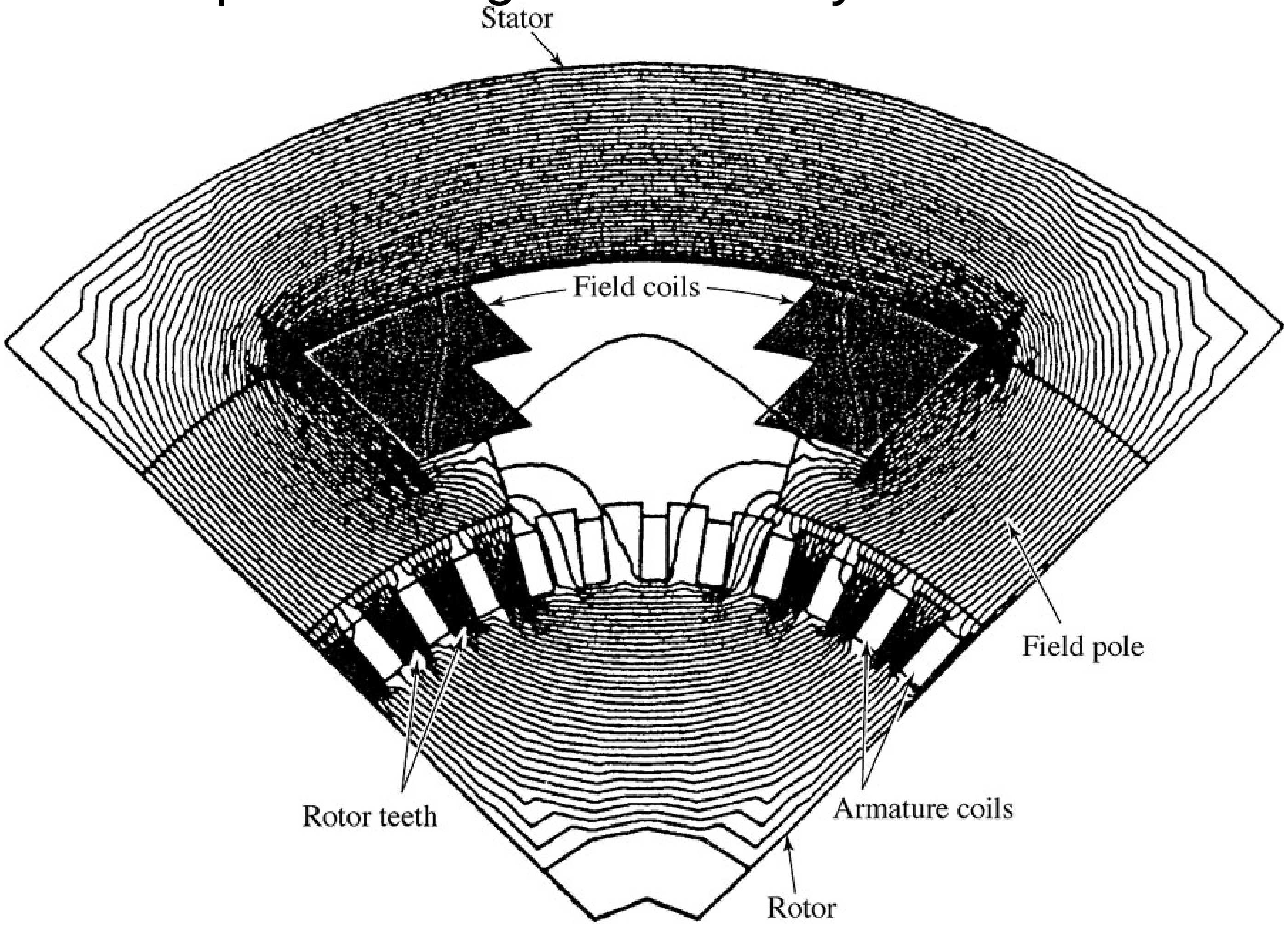
- Salient pole synchronous machine



(b)

FEA of Salient-Pole DC Generator

- Note that slot tips have high flux density

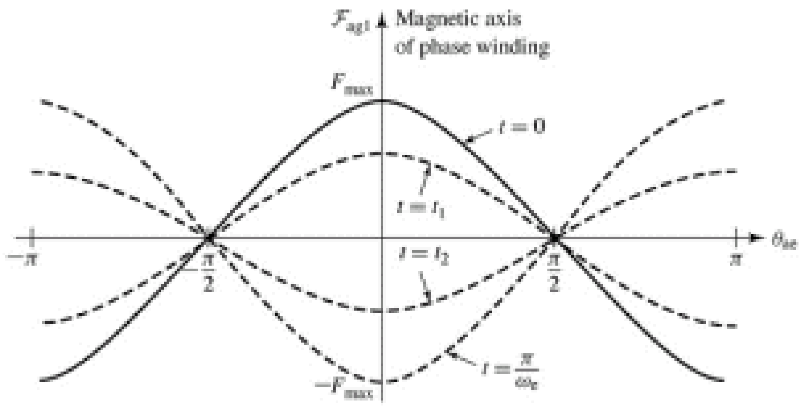


Excite Winding with AC Current

- What happens if we excite a single-phase winding with AC current?

Single phase winding

$$MMF = \left(\frac{4}{\pi}\right)\left(\frac{k_w N_{ph}}{poles}\right) i_a \cos\left(\frac{poles}{2}\theta_a\right)$$



What happens if we excite with AC curre

$$i_a = I\cos(\omega_e t)$$

ω_e = electrical frequency

kw=winding factor
Nph=number of series turns per phase

$$MMF = F_{\max}\cos\left(\frac{poles}{2}\theta_a\right)\cos(\omega_e t)$$

- This waveform remains fixed in space and has a time-varying amplitude

Excite Winding with AC Current

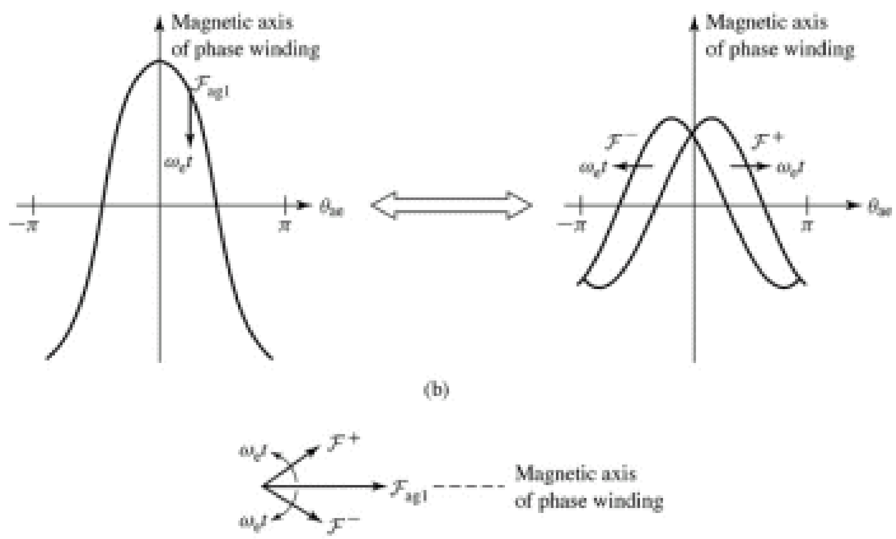
- Trigonometric identity:

$$\cos(\alpha)\cos(\beta) = \frac{1}{2}\cos(\alpha-\beta) + \frac{1}{2}\cos(\alpha+\beta)$$

- Re-write MMF using this trig identity:

$$MMF = \frac{F_{\max}}{2}\left\{\cos\left(\frac{poles}{2}\theta_a + \omega_e t\right) + \cos\left(\frac{poles}{2}\theta_a - \omega_e t\right)\right\}$$

- This is the sum of a cw-going wave and a ccw-going wave



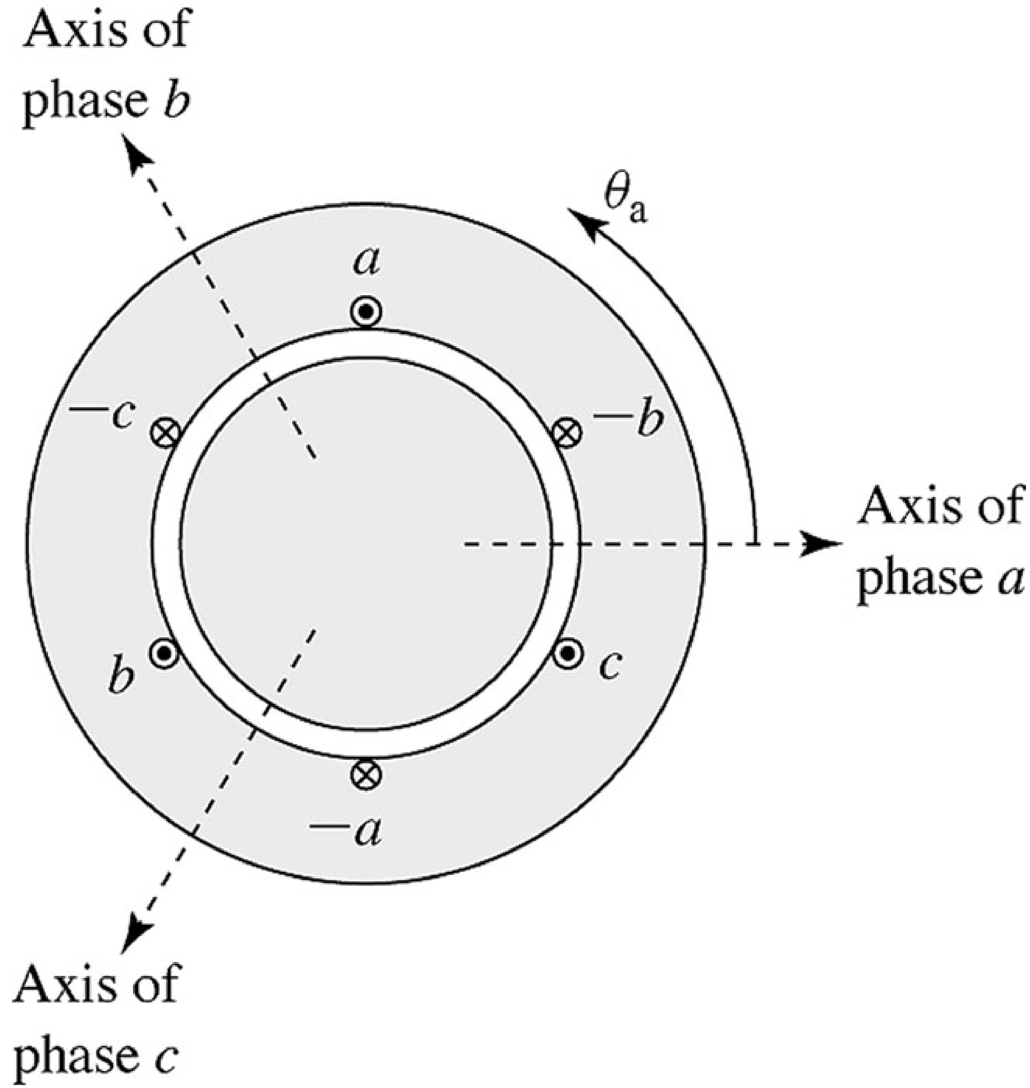
Simplified 2-Pole, 3-Phase Stator Winding

- Axis of phase a is where maximum flux is due to current in a winding
- For balanced 3-phase excitation:

$$i_a = I\cos(\omega_e t)$$

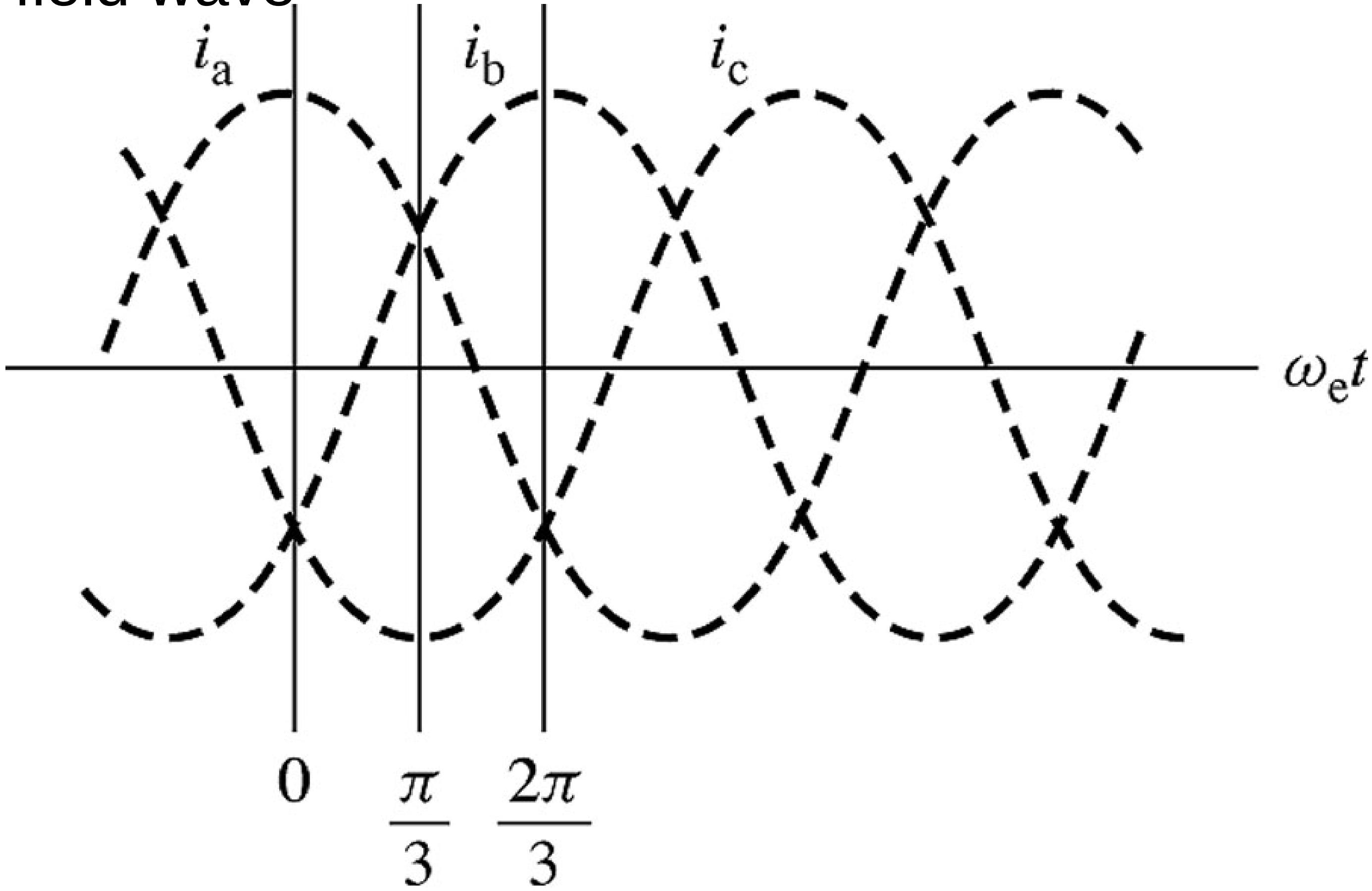
$$i_b = I\cos(\omega_e t - 120^o)$$

$$i_c = I\cos(\omega_e t - 240^o)$$



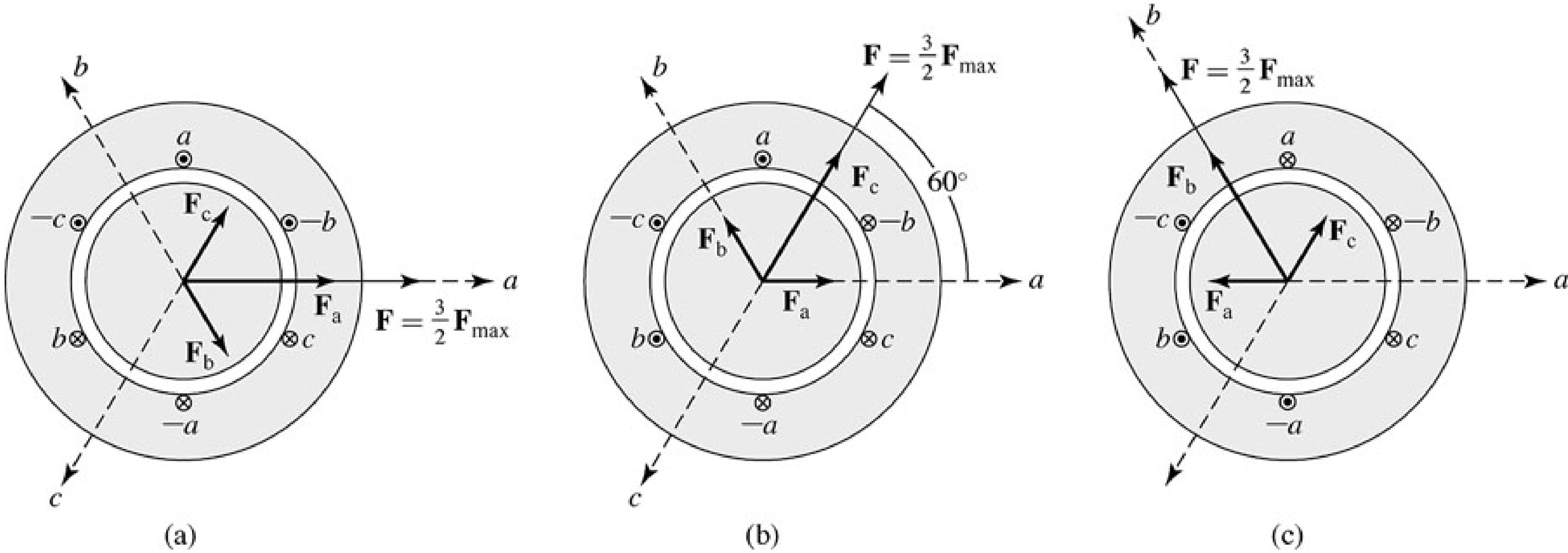
Phase Currents Under Balanced Load

- Under a balanced load, magnitude of phase currents are equal
- We'll next show that balanced currents cause a rotating magnetic field wave



Producing Rotating Magnetic Field with 3-Phase Currents

- Balanced 3 phase currents produce a rotating wave in the motor
- In this case, the magnetic field wave rotates counter-clockwise



Mathematics --- Part 1

- Find the MMFs for the 3 phases a, b and c

For phase a:

$$F_{A1} = F_{A1}^{+} + F_{A1}^{-} = \frac{1}{2} F_{\max} \left[\cos\left(\theta_{ae} - \omega_e t\right) + \cos\left(\theta_{ae} + \omega_e t\right) \right]$$

For phase b:

$$F_{B1} = F_{B1}^{+} + F_{B1}^{-} = \frac{1}{2} F_{\max} \left[\cos\left(\theta_{ae} - \omega_e t\right) + \cos\left(\theta_{ae} + \omega_e t + 120^{o}\right) \right]$$

For phase c:

$$F_{C1} = F_{C1}^{+} + F_{C1}^{-} = \frac{1}{2} F_{\max} \left[\cos\left(\theta_{ae} - \omega_e t\right) + \cos\left(\theta_{ae} + \omega_e t - 120^{o}\right) \right]$$

Mathematics --- Part 2

- Find sum of MMFs for the 3 phases

$$F_{total} = \frac{3}{2} F_{\max} \cos(\theta_{ae} - \omega_e t)$$

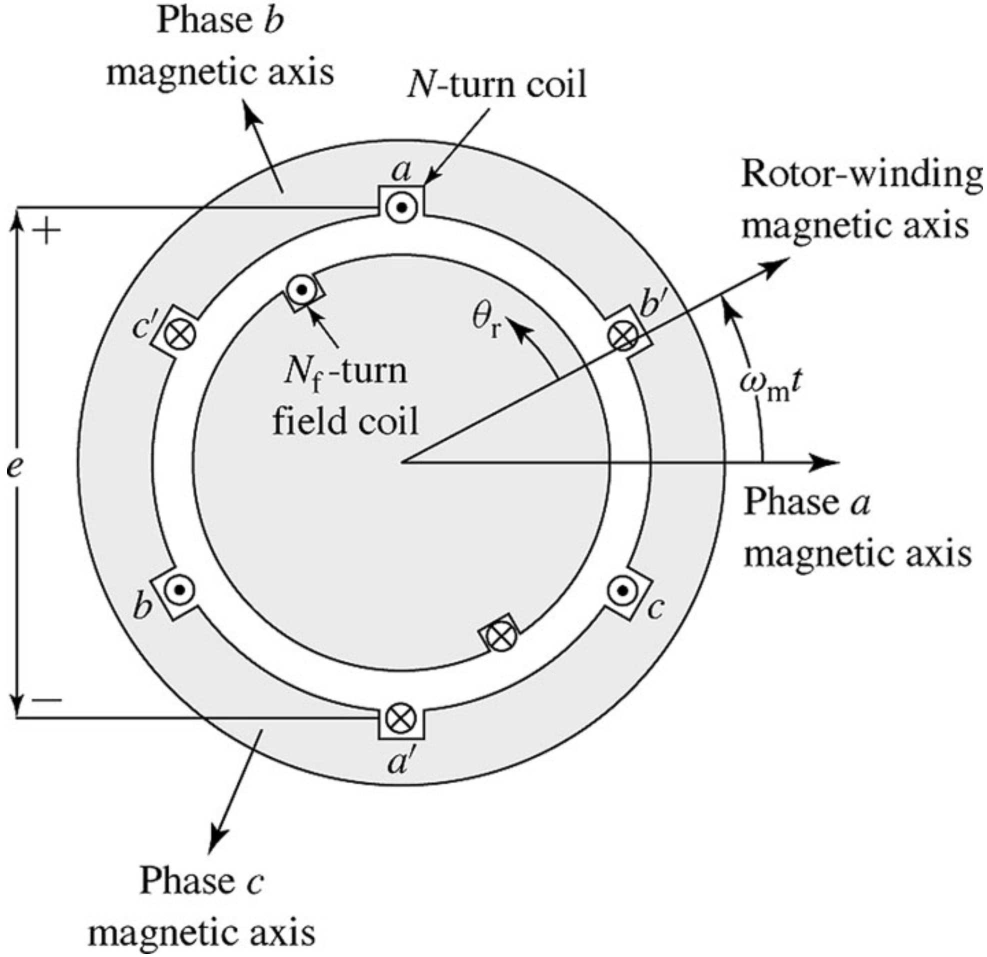
$$+ \frac{F_{\max}}{2} \left[\cos(\theta_{ae} + \omega_e t) + \cos(\theta_{ae} + \omega_e t + 120^o) + \cos(\theta_{ae} + \omega_e t - 120^o) \right]$$

The second term vector sums to zero, so:

$$F_{total} = \frac{3}{2} F_{\max} \cos(\theta_{ae} - \omega_e t)$$

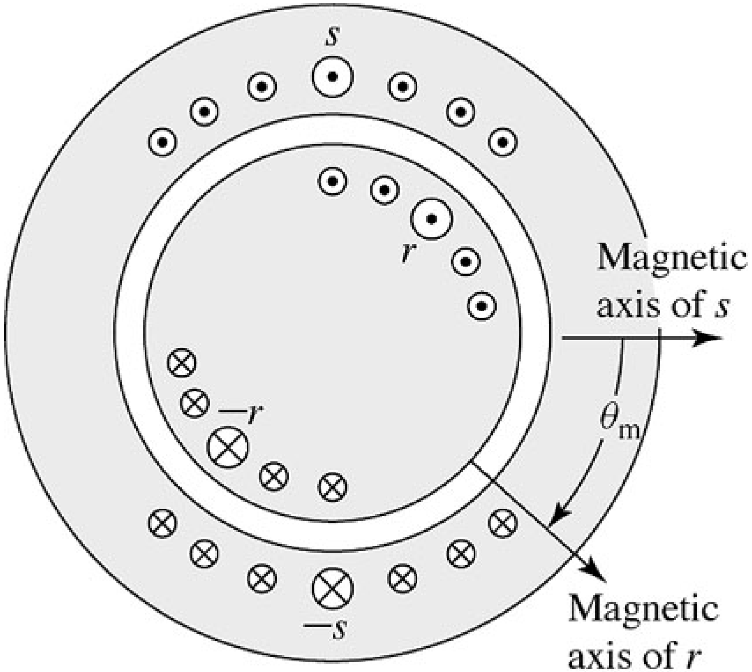
3-Phase AC Machine

• Generic AC machine; balanced 3-phase windings produce rotating magnetic field

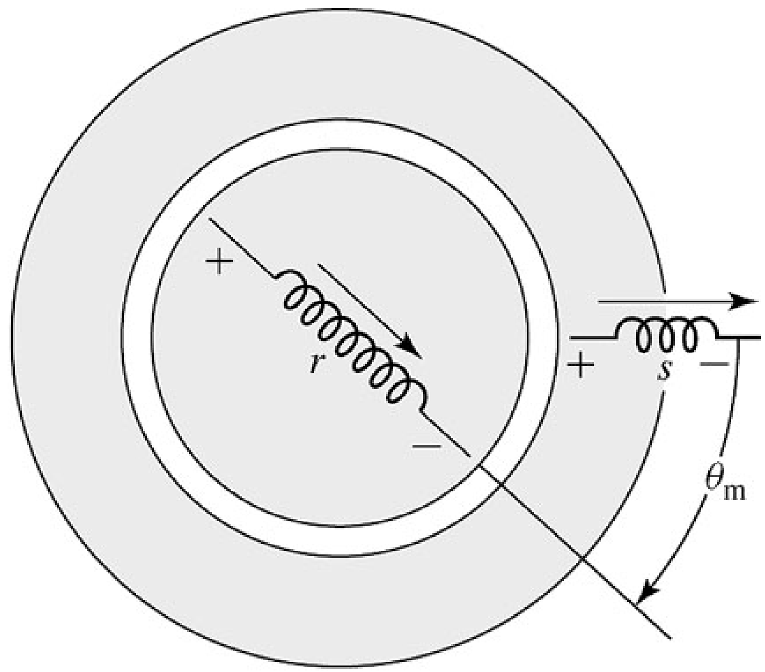


Two-Pole Machine

• In the circuit representation, we write the inductance matrix. From the inductance matrix, we can find the torque (similarly to what we did earlier)



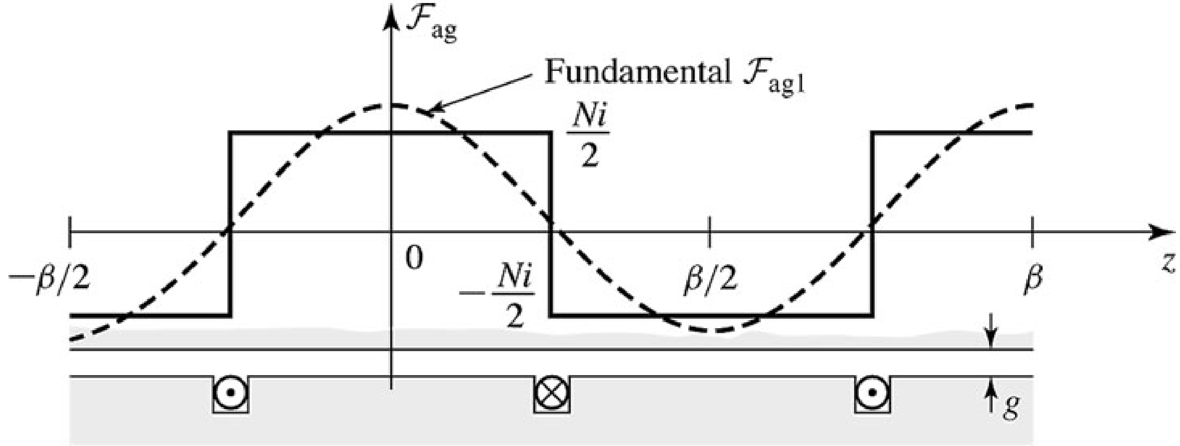
(a)



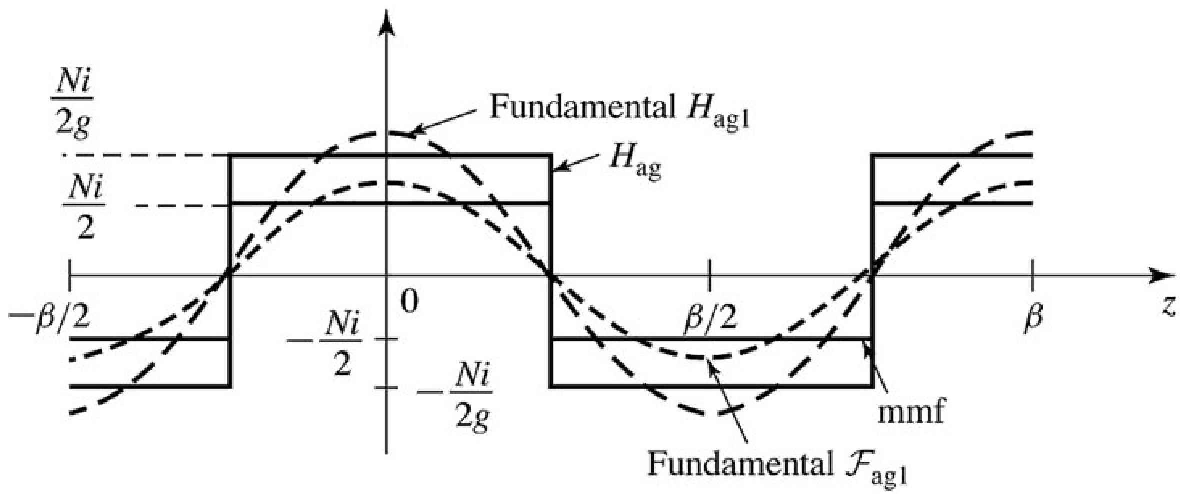
(b)

Linear Machine

- Analyzed in fundamentally the same way as a rotating machine

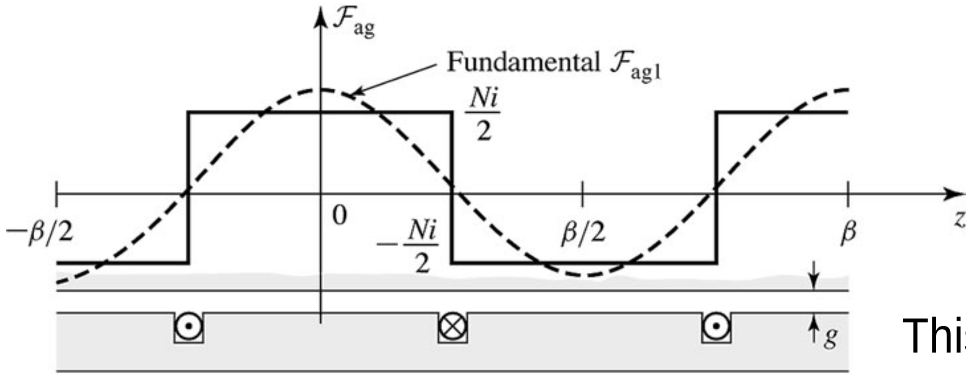


(a)

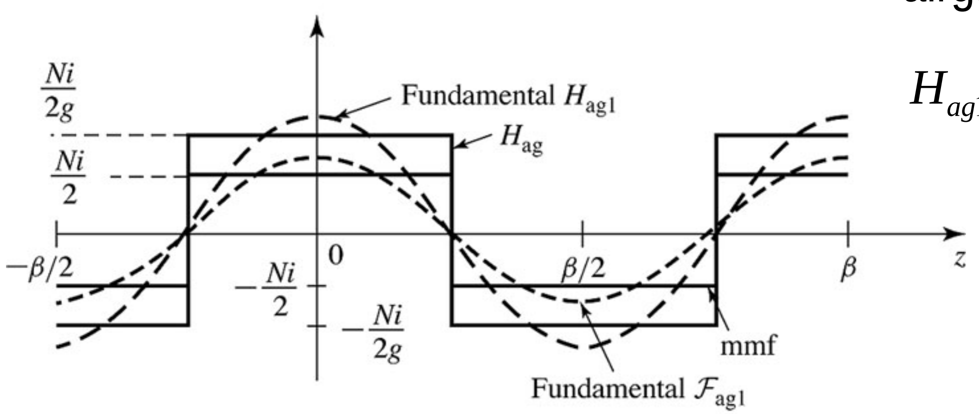


(b)

Linear Machine



(a)



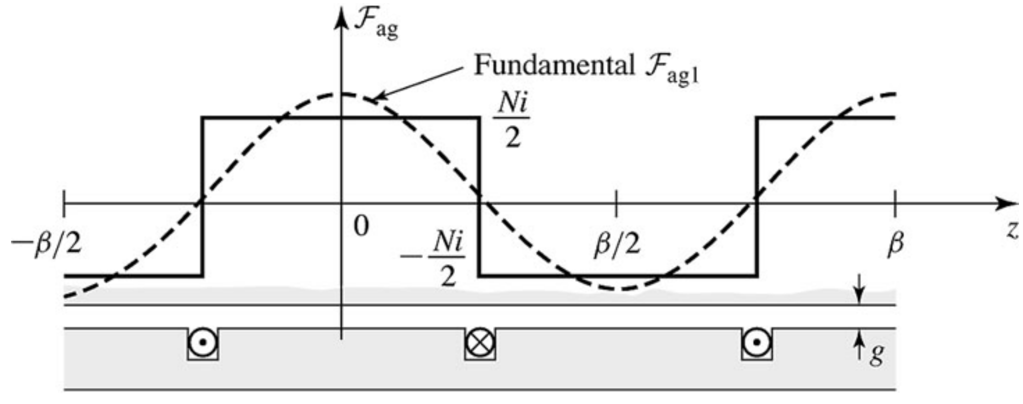
(b)

This motor has N_{ph} turns distributed over p periods in z. The fundamental component of airgap MMF is:

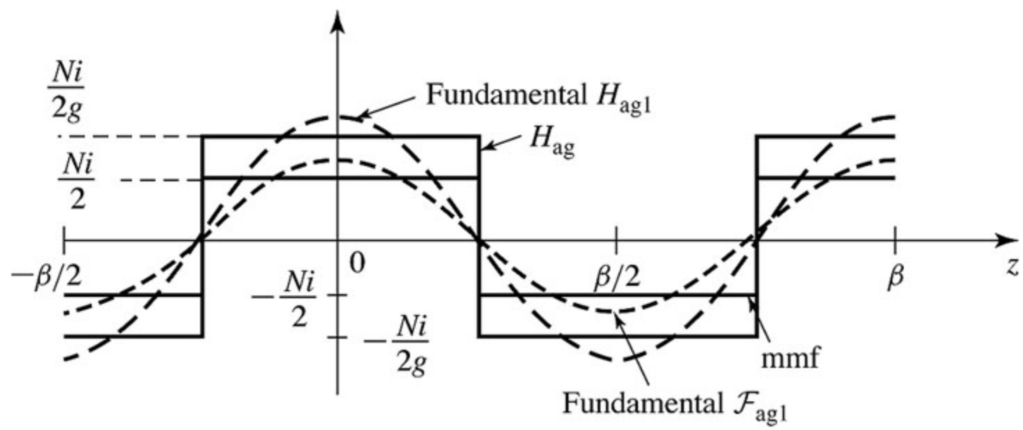
$$H_{ag1} = \left(\frac{4}{\pi}\right)\left(\frac{k_w N_{ph} i}{2pg}\right)\cos\left(\frac{2\pi z}{\beta}\right)$$

Linear Machine

- Three phase linear winding can be made with 3 windings, with each phase displaced in position by β/3, and excited with balanced 3-phase currents
- This results in a MMF wave that travels in the +z direction with linear velocity $f_e\ \beta$



(a)



(b)

Linear Machine MMF Wave

Balanced 3-phase excitation

$$i_a = I_m \cos\omega_e t$$

$$i_b = I_m \cos(\omega_e t - 120^o)$$

$$i_c = I_m \cos(\omega_e t - 240^o)$$

Following the development for the rotary motor,we find that there is a positive-traveling MMF wave:

$$F^+(z,t) = \frac{3}{2} F_{\max} \cos\left(\frac{2\pi z}{\beta} - \omega_e t \right)$$

$$F_{\max} = \left(\frac{4}{\pi} \right) \frac{k_w N_{ph}}{2p} I_m$$

Example: Linear Machine

• *Fitzgerald*, Example 4.9

• A three-phase linear AC motor has a winding with wavelength β = 0.5m and an air gap of g = 1.0 cm in length. A total of 45 turns, with a winding factor k_w = 0.92 are distributed over a total winding length of 3β = 1.5m. Assume that the windings are excited with balanced 3-phase currents of peak amplitude 700A and frequency 25 Hz.

• Calculate (a) amplitude of the MMF wave; (b) Corresponding air-gap flux density; and (c) the velocity of the traveling MMF wave

Example: Linear Machine --- Solution

(a) The amplitude of the MMF wave is:

$$F_{peak} = \left(\frac{3}{2}\right)\left(\frac{4}{\pi}\right)\left(\frac{k_w N_{ph}}{2p}\right) I_m$$

$$= \left(\frac{3}{2}\right)\left(\frac{4}{\pi}\right)\left(\frac{0.92 \times 45}{2 \times 3}\right)(700)$$

$$= 8810\ A/m$$

(b) Peak airgap flux density is found from the MMF by dividing by airgap g and multiplying by μ_o

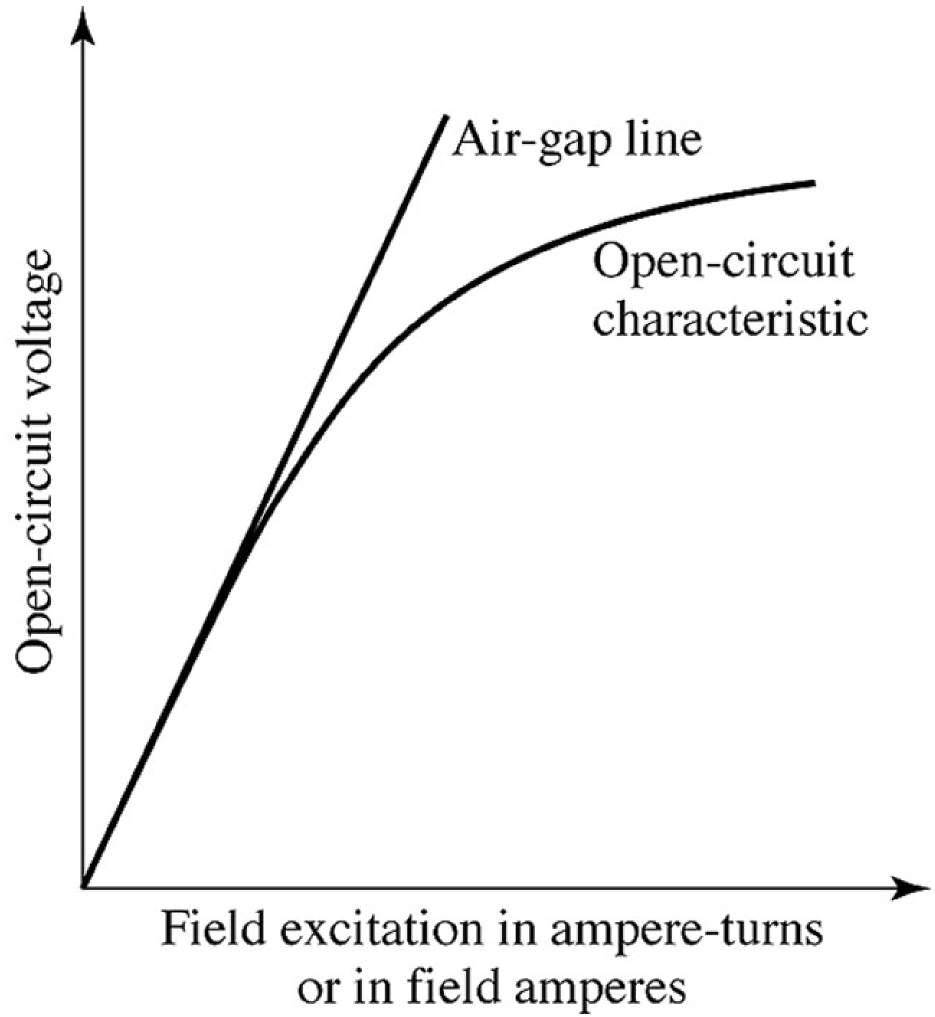
$$B_{peak} = \frac{\mu_o F_{peak}}{g} = \frac{(4\pi \times 10^{-7})(8810)}{0.01} = 1.11\,T$$

(c) Velocity of the traveling wave is:

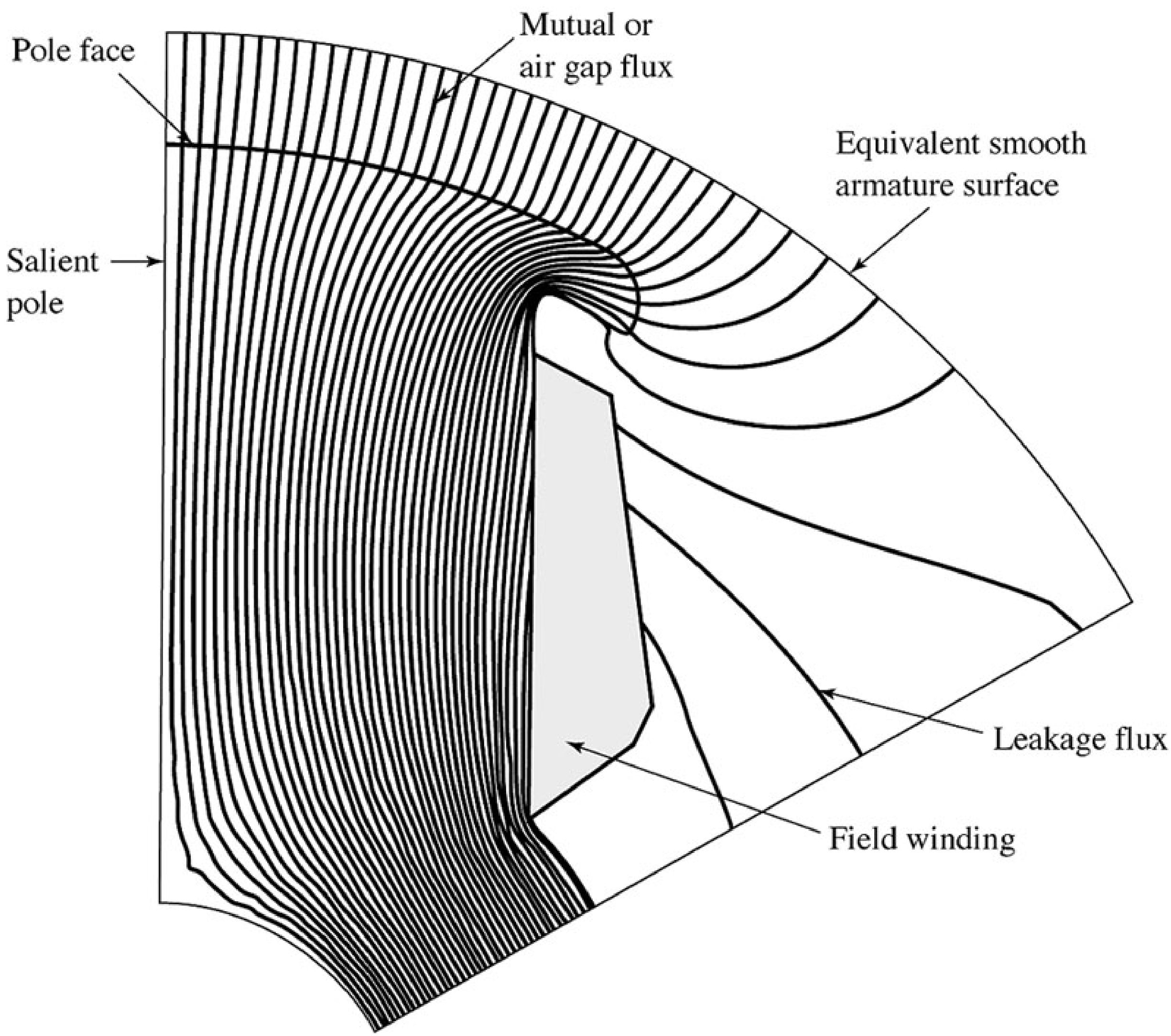
$$v = f_e \beta = (25)(0.5) = 12.5\ m/s$$

Magnetic Saturation Effects

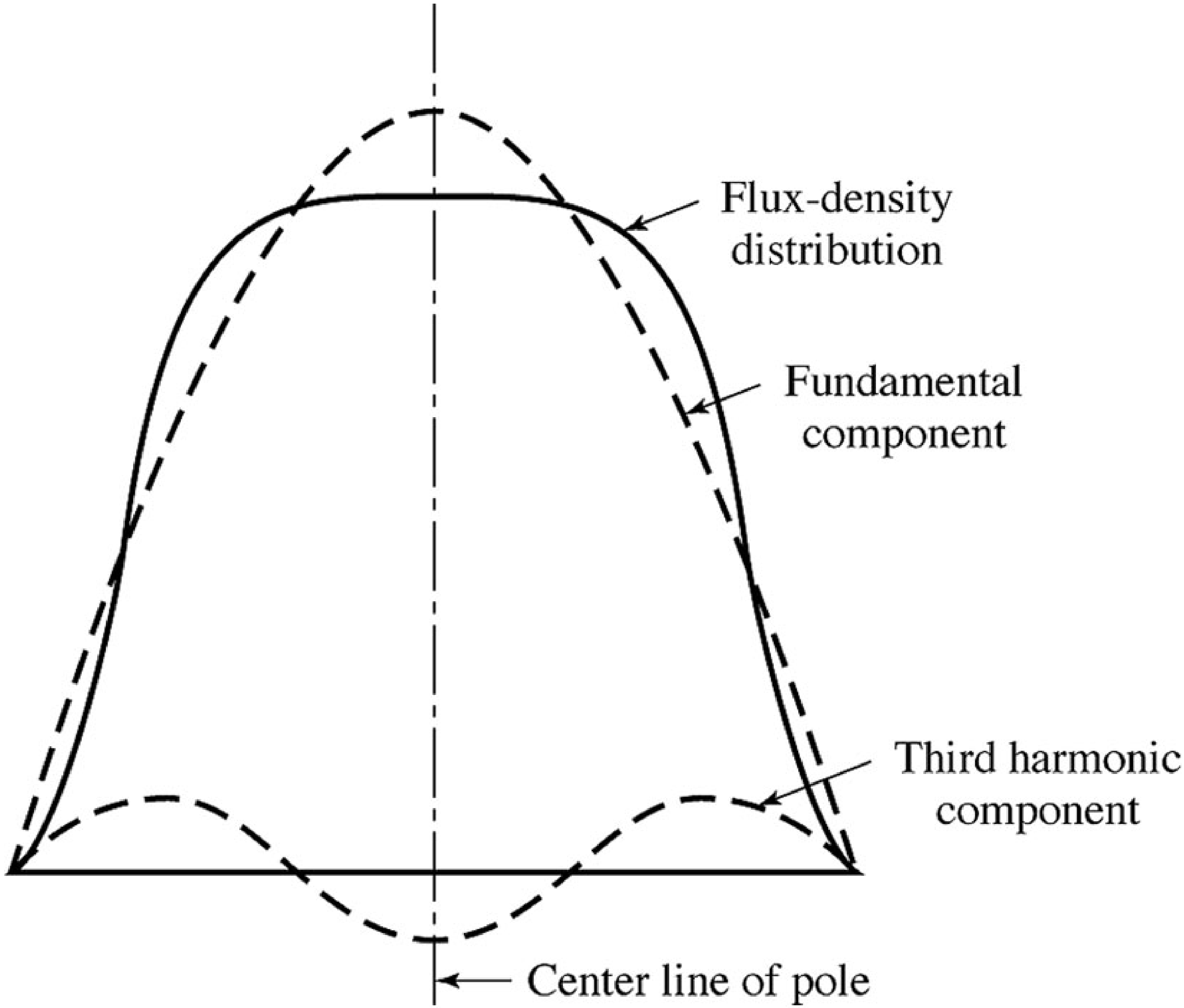
- Saturation causes less-than-expected voltage at high level of field current excitation
- "Air-gap line" is curve if saturation does not occur



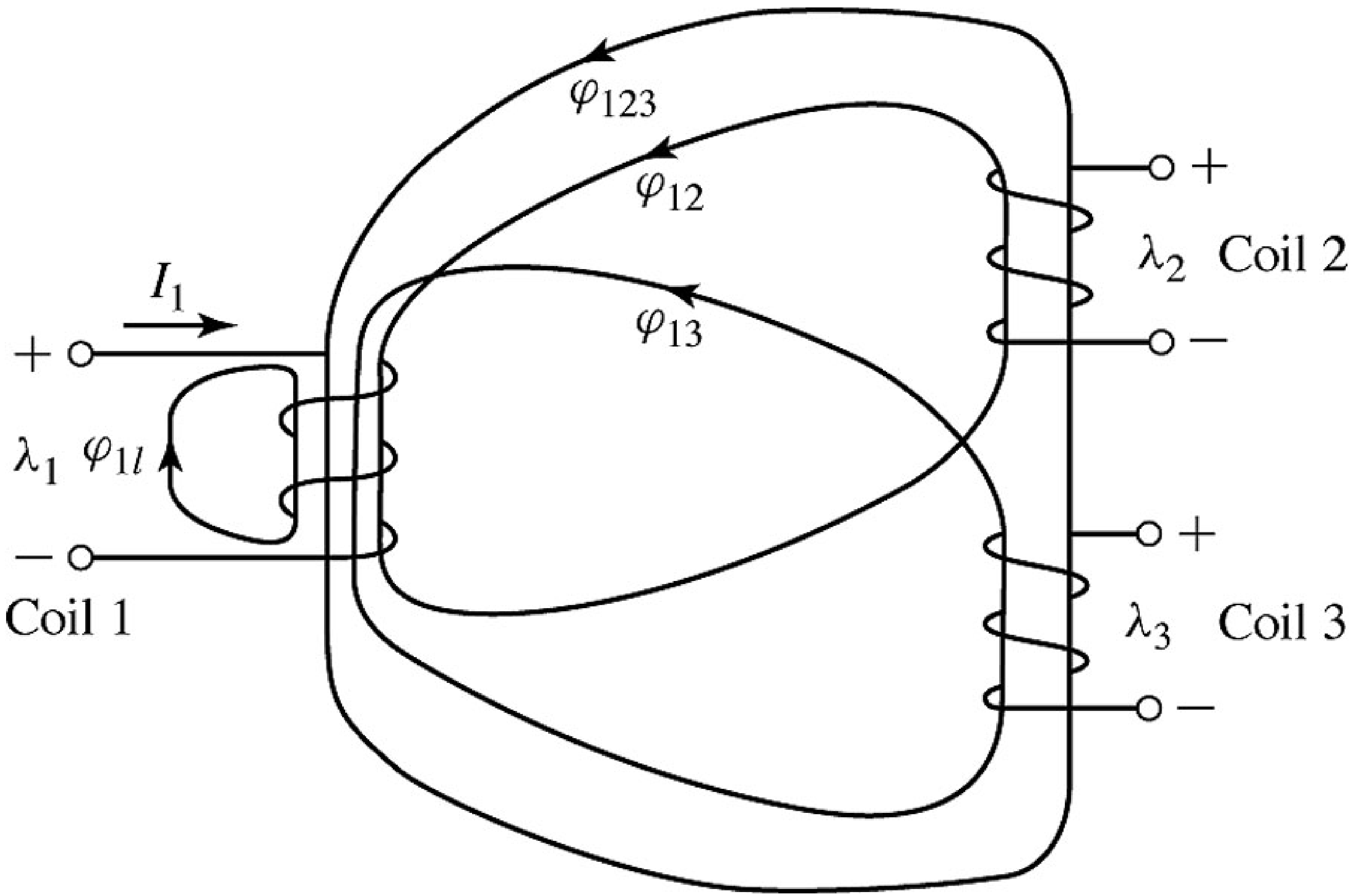
FEA on Salient Pole



Flux Density of Salient Pole

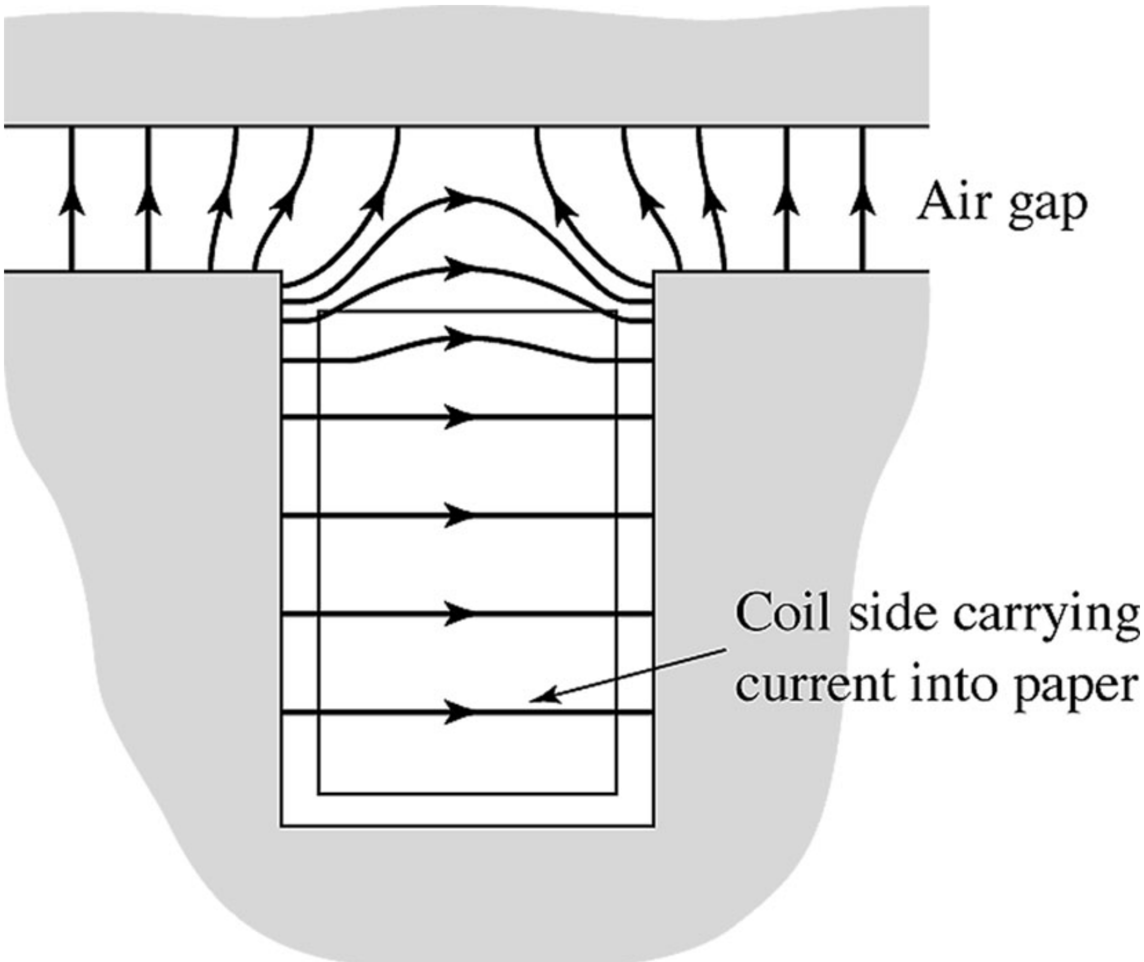


Leakage Flux



Coil in Slot

- Flux crossing the slot is a component of leakage flux



Synchronous Machines --- Overview

- Elementary concepts
- Inductance and equivalent circuits
- Open and short-circuit characteristics
- Steady state power angle
- Salient poles
- Power angle in salient pole machines
- Use of permanent magnets

Synchronous Machines --- Overview

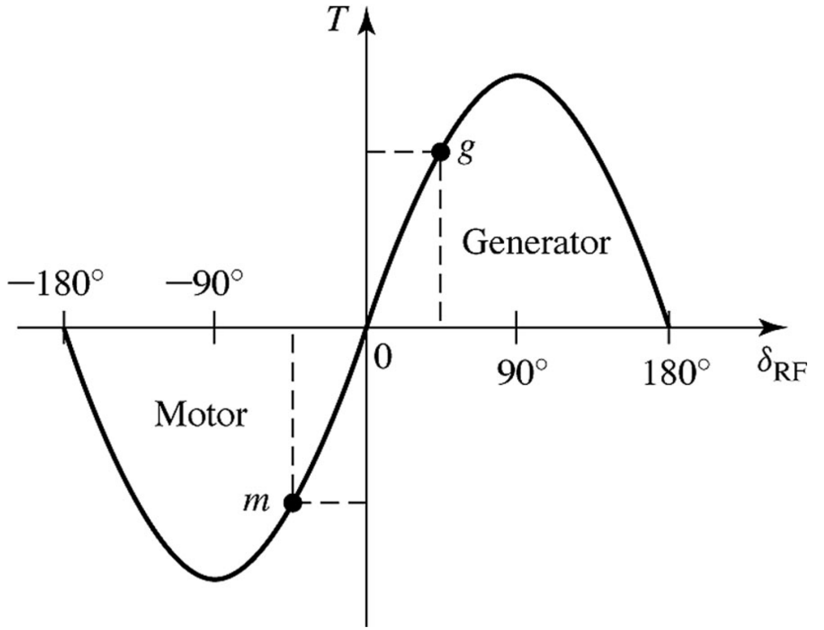
- AC current flows in the armature winding, and DC excitation is supplied to the field winding
- Armature winding almost always is on the stator, and is a three-phase winding
- Field winding is on the rotor

Torque-Angle Characteristic

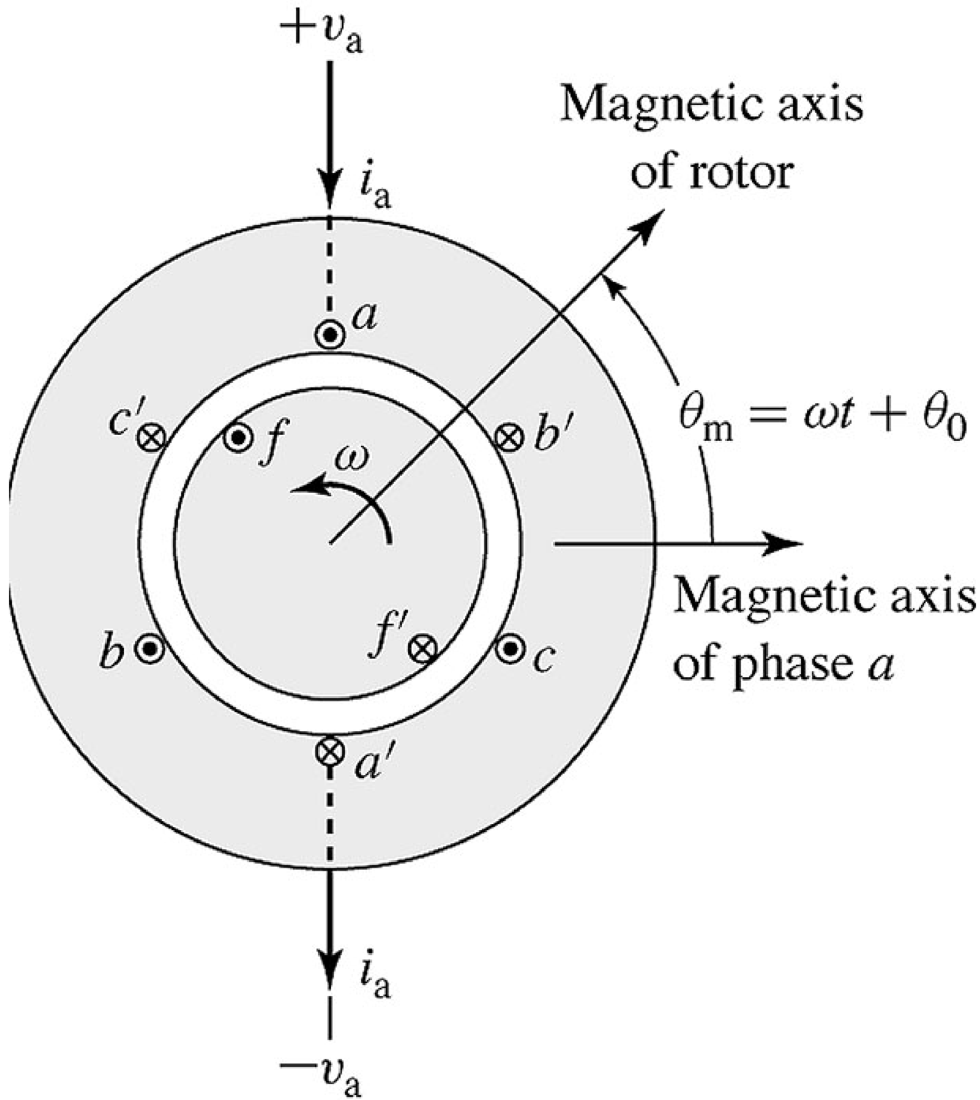
Torque produced by a synchronous machine:

$$T = \left(\frac{\pi}{2}\right)\left(\frac{poles}{2}\right)^2 \Phi_R F_f \sin\delta_{RF}$$

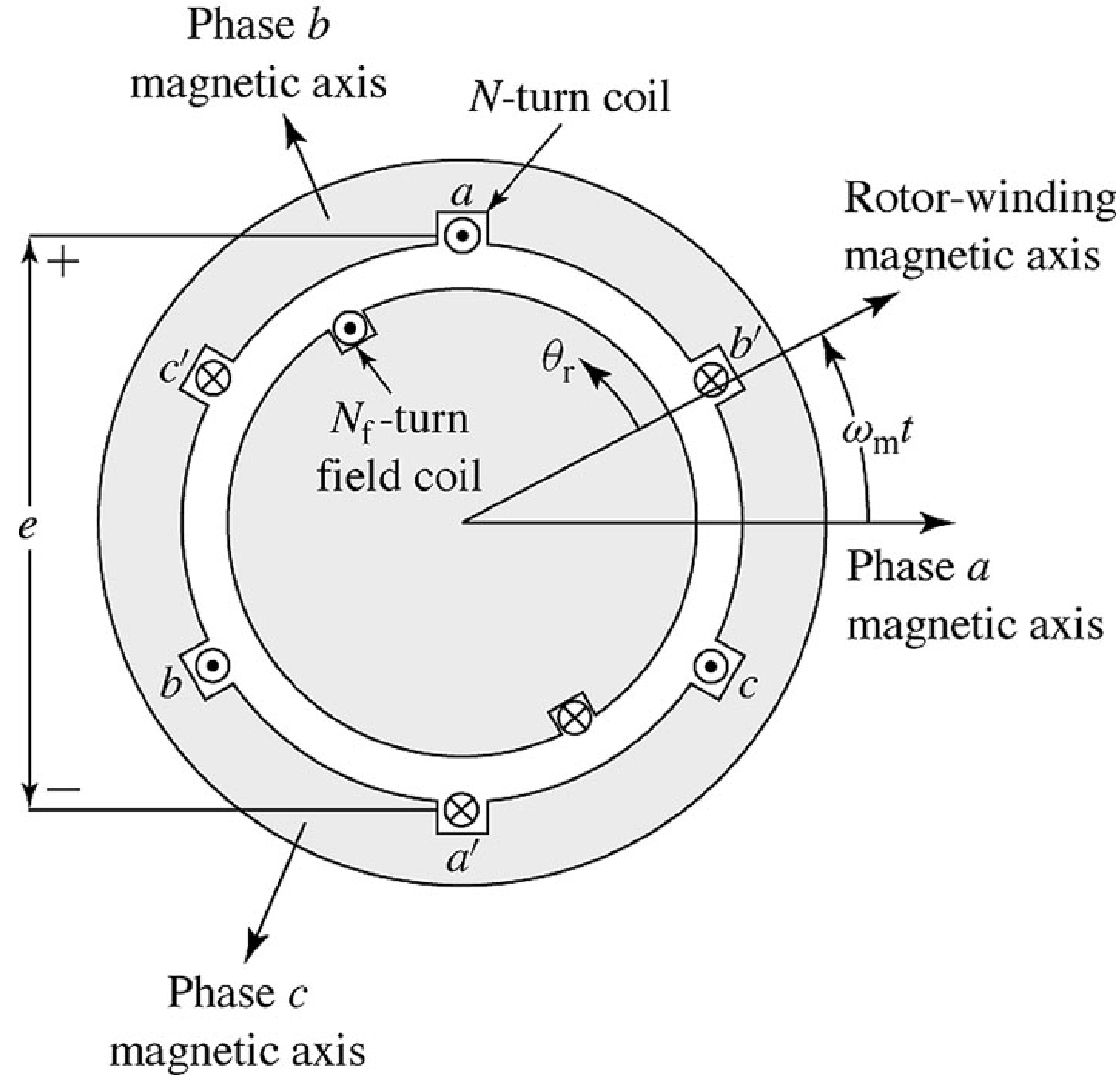
Φ_R=air-gap flux per pole
F_f = MMF of the field winding
δ_{RF}=electrical phase angle between magnetic axes of Φ_R and F_f



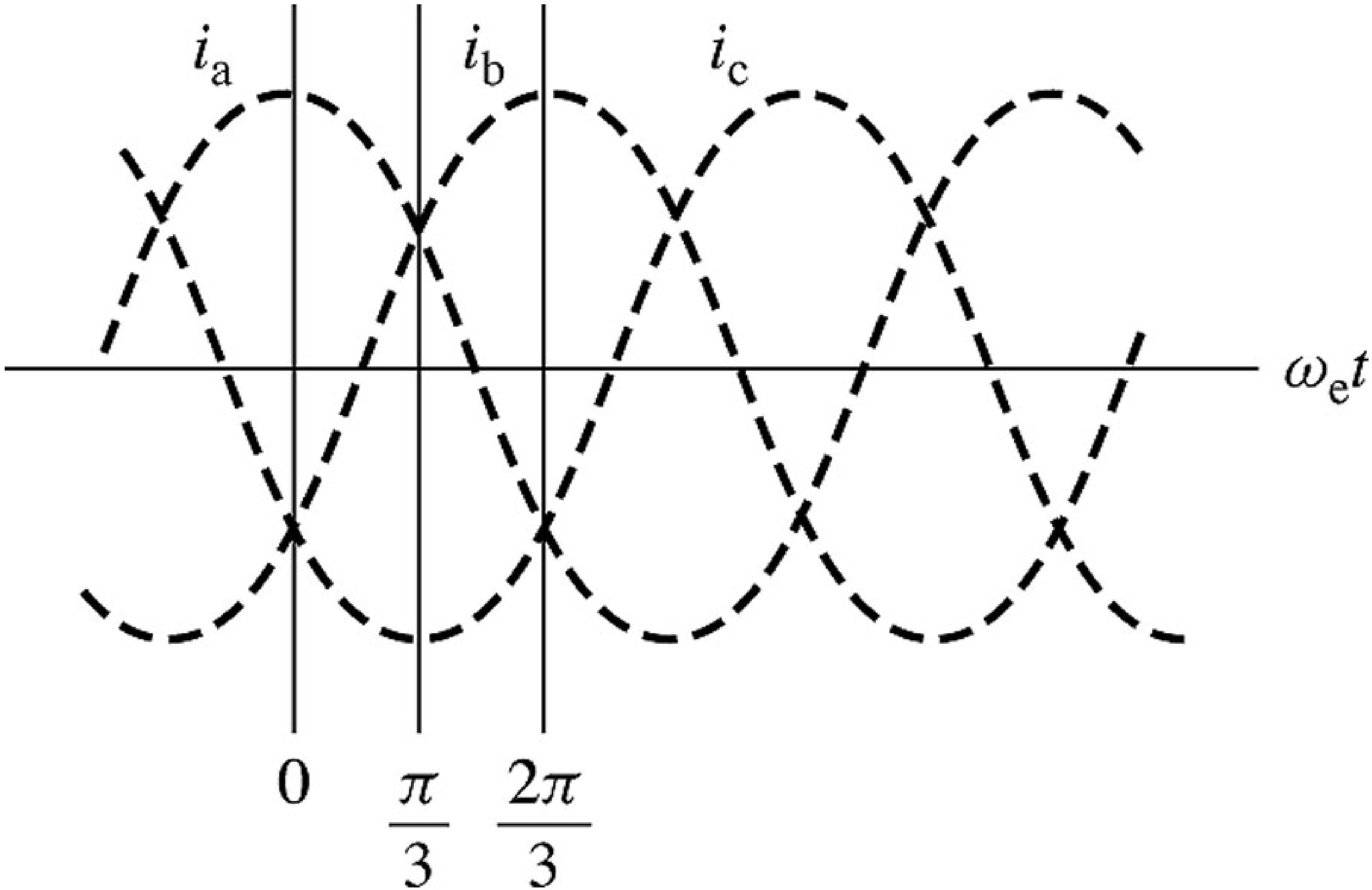
2-Pole, 3 Phase Synchronous Machine



3-Phase AC Machine



Phase Currents Under Balanced Load

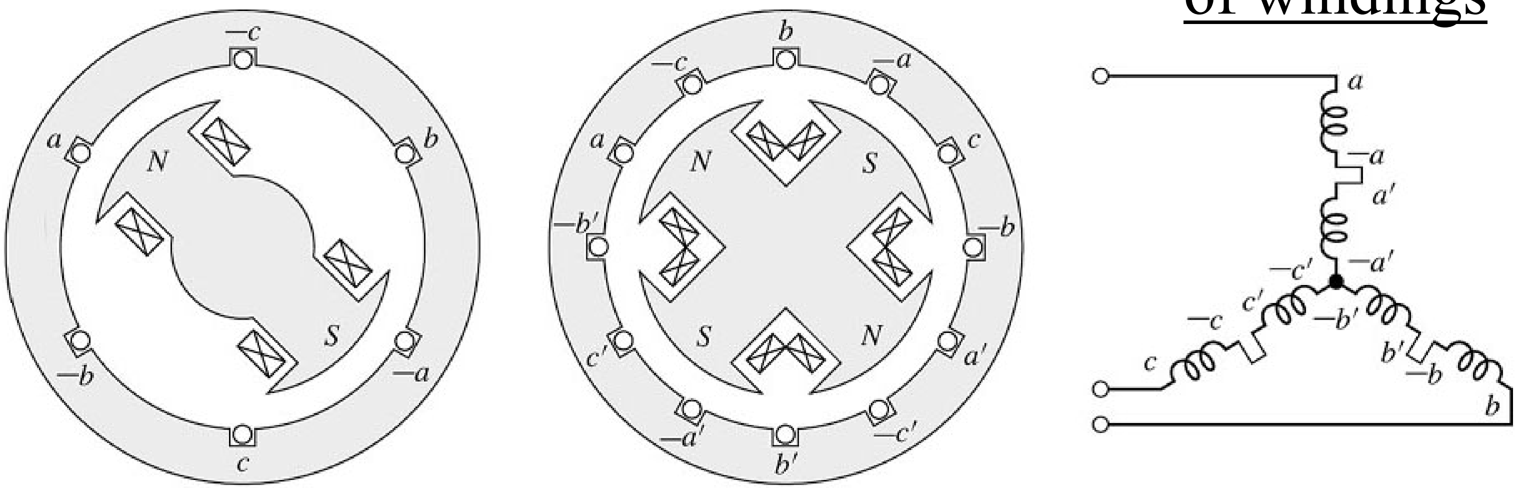


Three-Phase Generators

2-pole

4-pole

Y-connection of windings

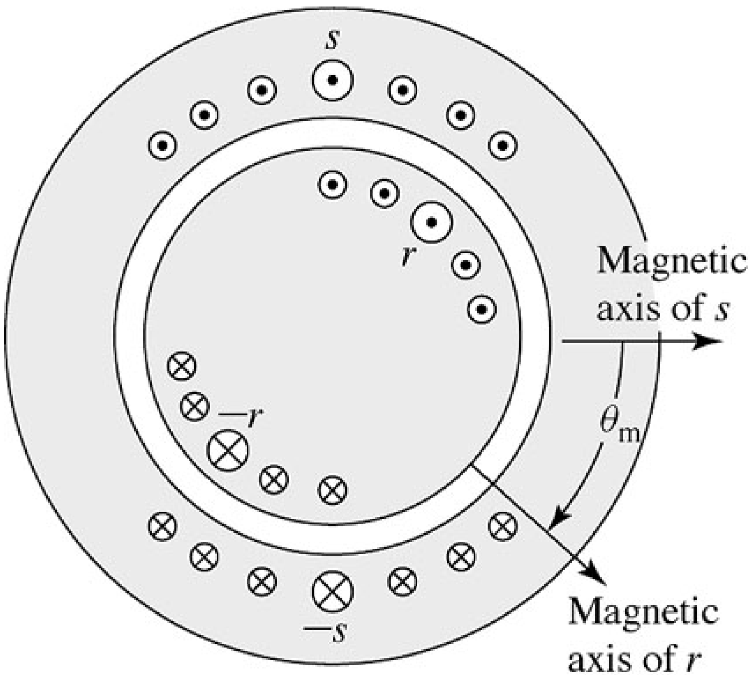


(a) (b) (c)

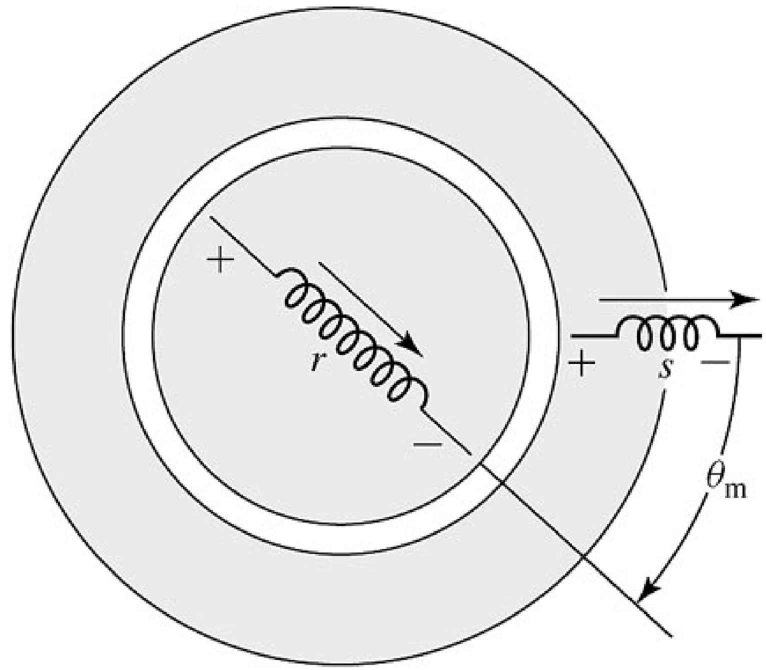
Two-Pole Machine

-Windings

-Inductance point-of-view

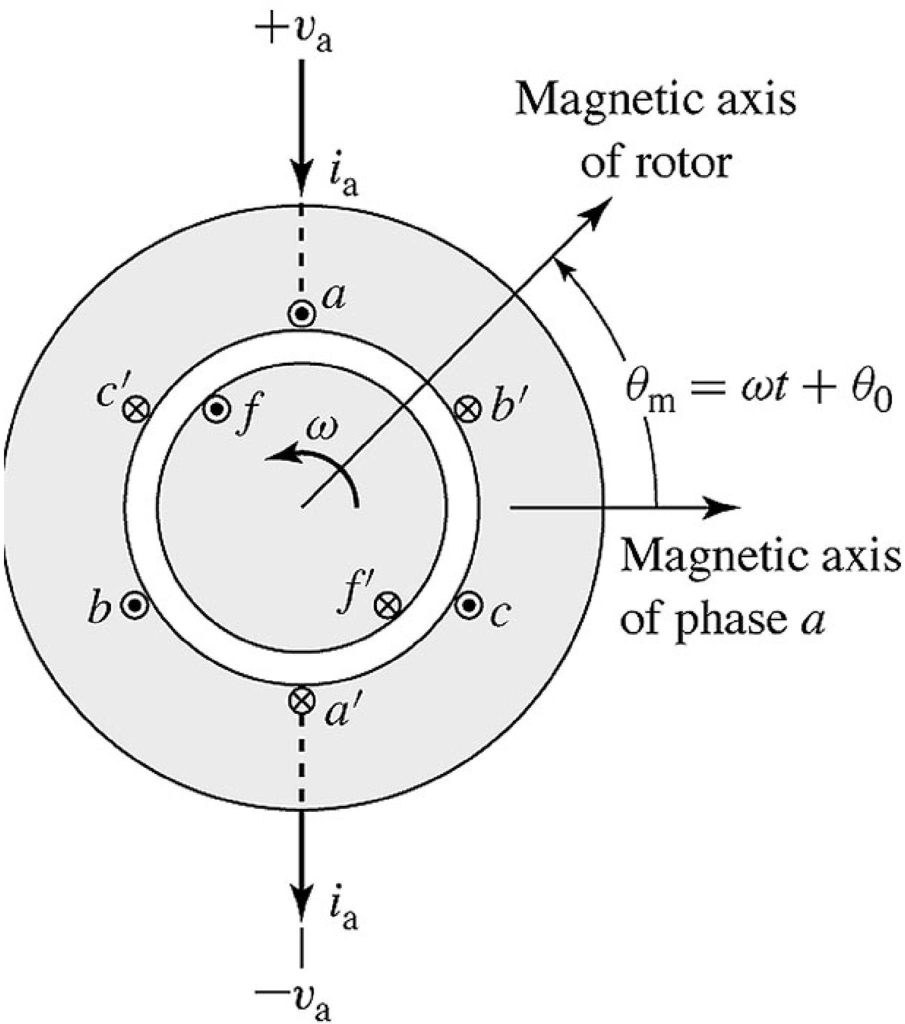


(a)



(b)

Two-Pole Machine



Flux linkages with phases a, b, c and field

$$\lambda_a = L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + L_{af} i_f$$
$$\lambda_b = L_{ba} i_a + L_{bb} i_b + L_{bc} i_c + L_{bf} i_f$$
$$\lambda_c = L_{ca} i_a + L_{cb} i_b + L_{cc} i_c + L_{cf} i_f$$
$$\lambda_f = L_{fa} i_a + L_{fb} i_b + L_{fc} i_c + L_{ff} i_f$$

Inductances may vary with rotary angle

Simplifying assumptions:
In cylindrical motor, self inductance of field winding L_{ff} is independent of angle

Stator self-inductances (L_{aa}, L_{bb}, L_{cc})
Don't vary with angle

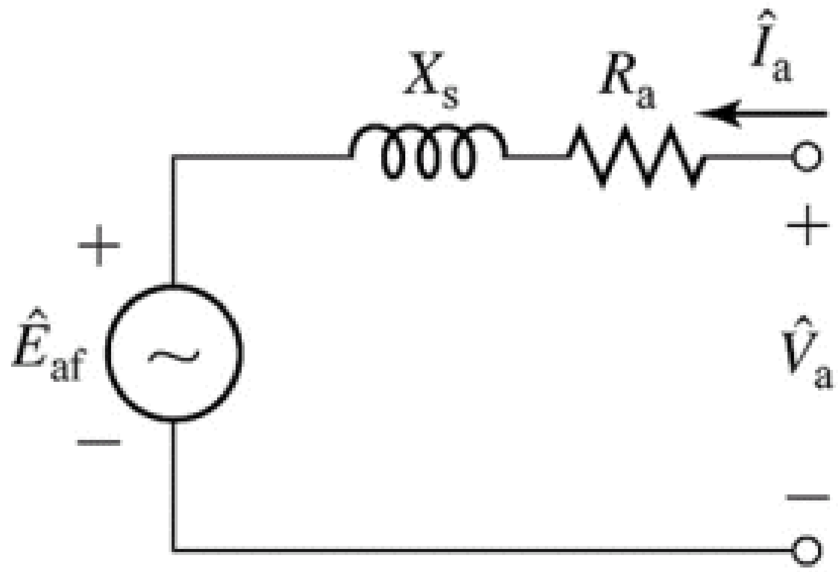
Mutual inductances ($L_{ab} = L_{ac} = L_{ca} = L_{ba}$, etc.)

Putting this all together, we get a relatively simple equivalent circuit, suitable for balanced
3-phase operation, ignoring leakage

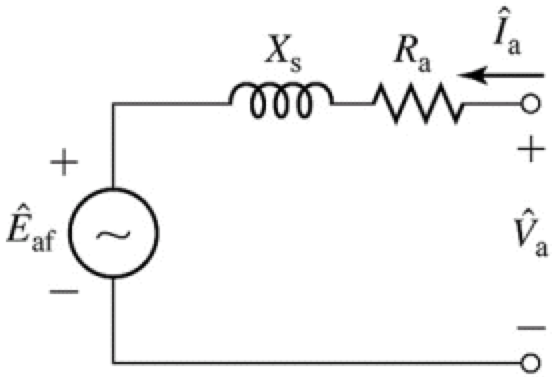
Synchronous Machine Equivalent Circuits

• The mathematical derivation of synchronous machine under balanced 3-phase excitation is shown in *Fitzgerald*, pp. 248-254

• We can model the electrical terminals, per phase, as an armature resistance, armature reactance, and voltage source corresponding to motor back-EMF



Synchronous Machine Equivalent Circuits



Summary of results for equivalent circuit:

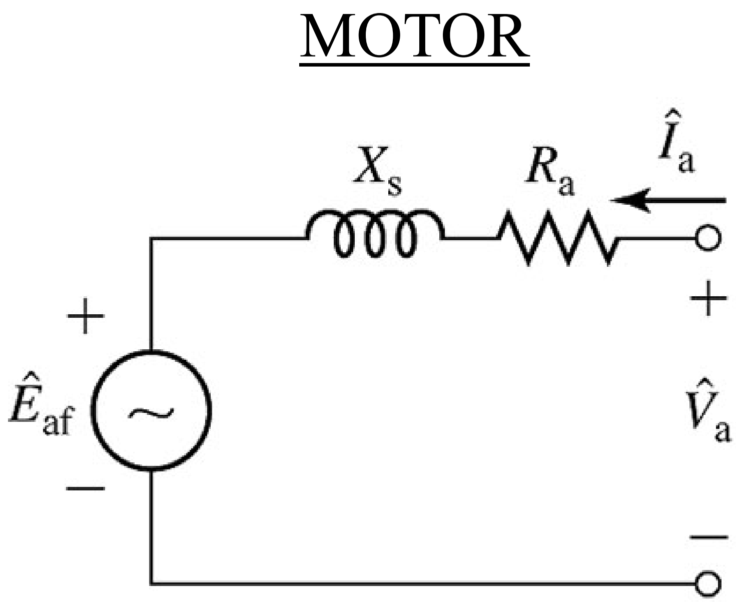
$$E_{af} = \frac{\omega_e L_{af} I_f}{\sqrt{2}}$$

L_{af} = stator to rotor mutual inductance
I_f = field winding current

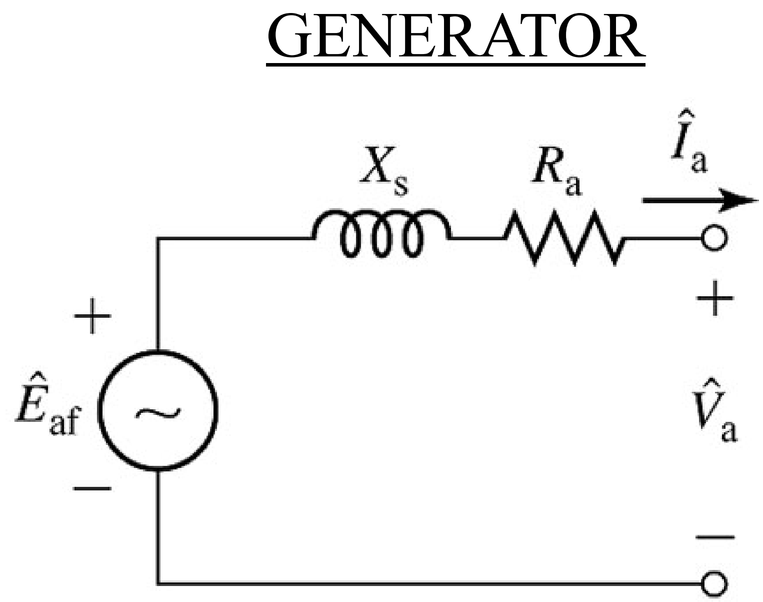
X_s = "synchronous reactance" which can be modeled as an inductance under balanced 3-phase excitation

R_a = armature winding resistance

Synchronous Machine Equivalent Circuits



(a)



(b)

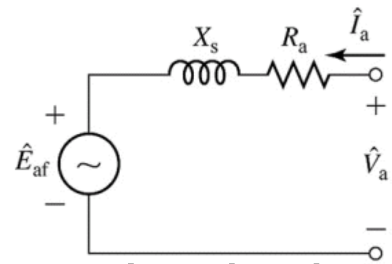
Example: Synchronous Machine

- *Fitzgerald*, Example 5.1
- A 60 Hz, 3 phase synchronous machine has a terminal voltage of 460V (line-line) and a terminal current of 120A at a power factor of 0.95 lagging. The field current is 47A. The synchronous reactance is 1.68 Ohms, and the armature resistance is negligible. Find (a) The generated voltage E_{af}

(b) The magnitude of the field-armature mutual inductance L_{af}; and

(c) The electrical power input to the motor in kilowatts and horsepower

Example: Synchronous Machine --- Solution



(a) Using the motor circuit, the generated voltage is:

$$E_{af} = V_a - jX_s I_a$$

V_a = 460V line-line, or 266V line-neutral

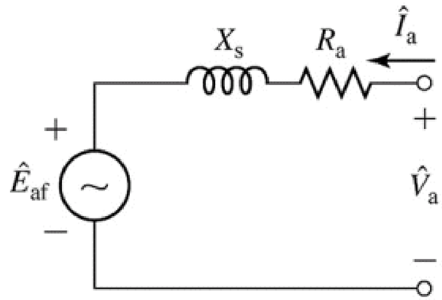
Lagging power factor means that the angle of the current is:

$$\theta = -\cos^{-1}(0.95) = -18.2^o$$

This means that the armature current is:

$$I_a = 120e^{-j18.2^o}$$

Example: Synchronous Machine --- Solution



We can convert this to Cartesian form, remembering that

$$e^{jx} = \cos x + j\sin x$$

$$e^{-j18.2^o} = \cos(-18.2^o) + j\sin(-18.2^o) = 0.95 - j(0.31)$$

Finally, we can find the generated voltage:

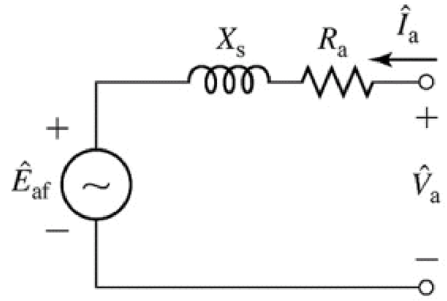
$$E_{af} = 266 - j(1.68)(120)(0.95 - j0.31)$$

After much mathematical manipulation,
(or by using MATLAB)

$$E_{af} = 203.5 - j(191.5)$$

$$= 279.4\angle -43.3^o$$

Example: Synchronous Machine --- Solution



(b) We find the field armature mutual inductance L_{af}:

$$L_{af} = \frac{\sqrt{2}E_{af}}{\omega_e I_f} = \frac{(\sqrt{2})(279.4)}{(2\pi \times 60)(47)} = 22.3\ mH$$

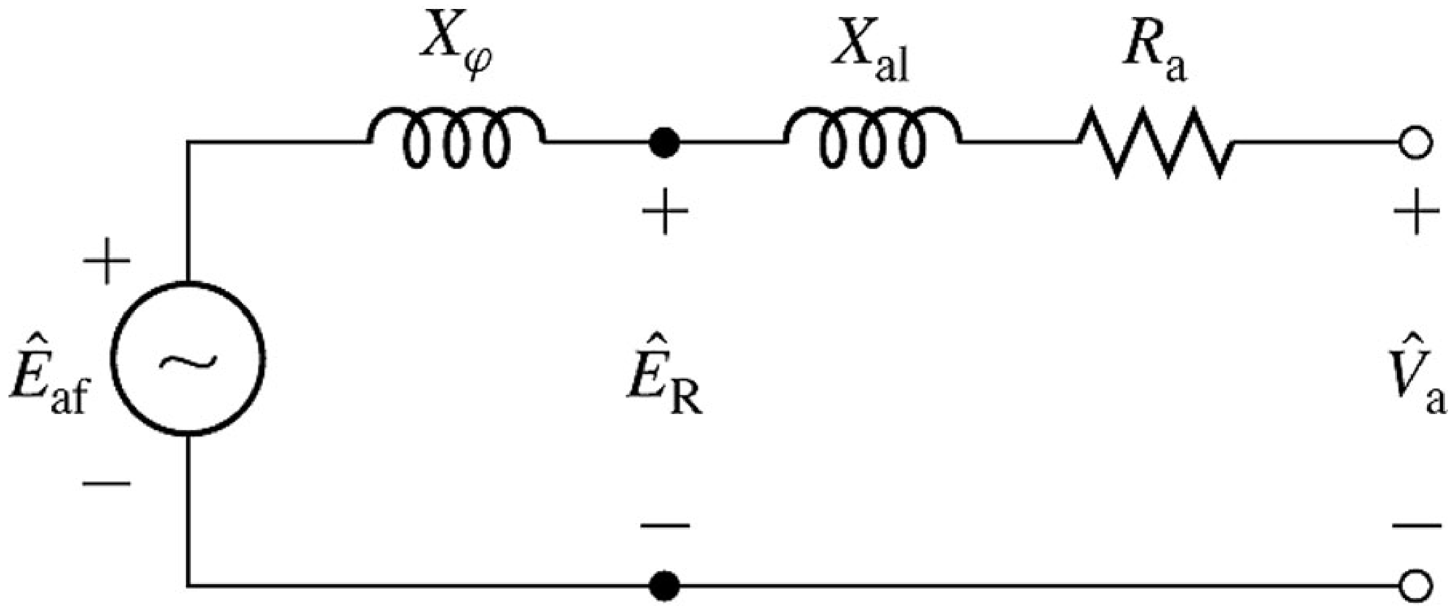
(c) The total motor electric power input is found by recognizing that the 3 phase power is 3 times that of the power input of a single phase, so:

$$P = (3)(V_a)(I_a)(PF)$$

$$= (3)(266)(120)(0.95)$$

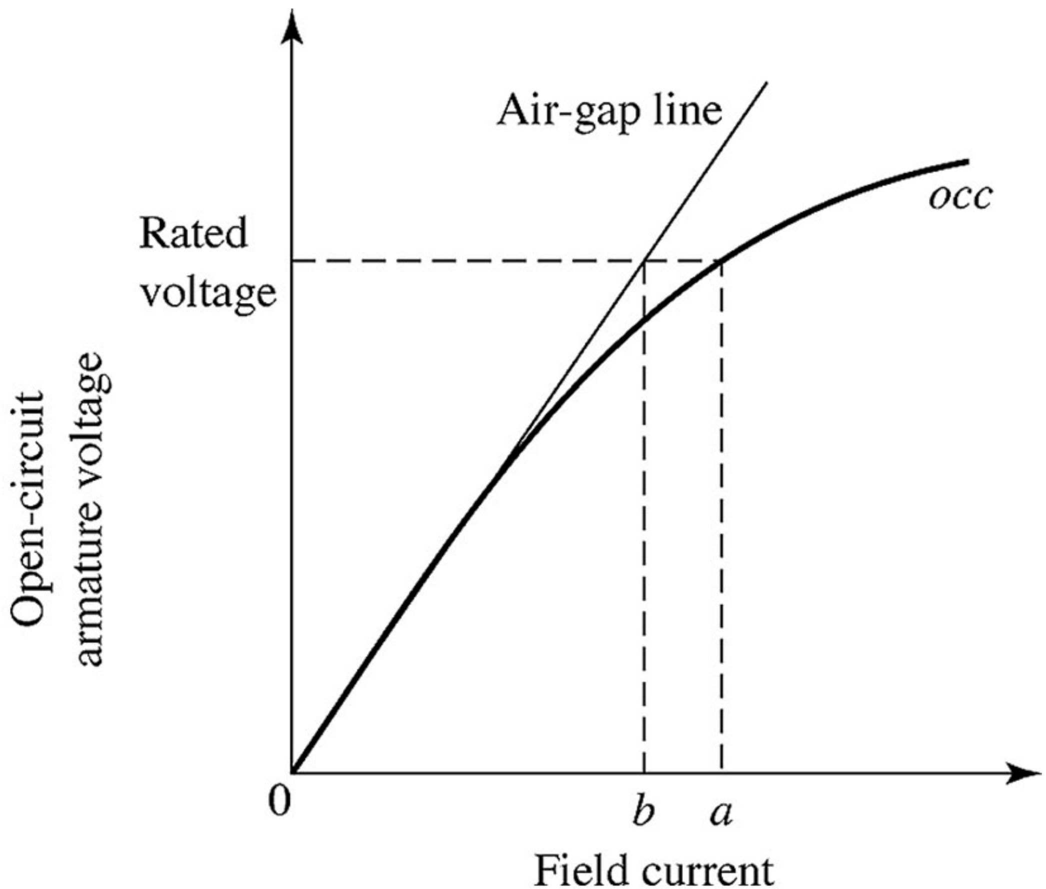
$$= 91\ kW = 122\ hp$$

Synchronous Machine Equivalent Circuit Showing Leakage



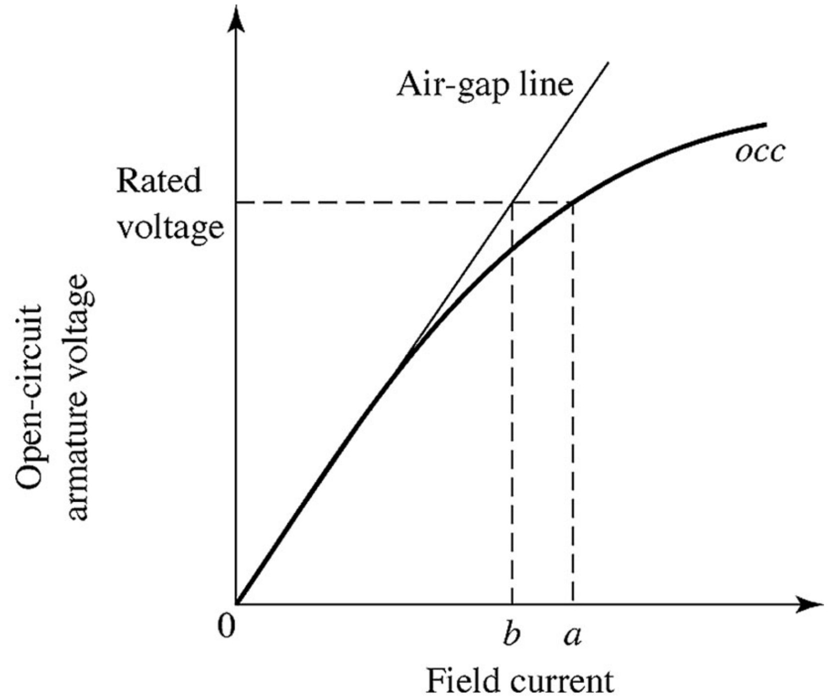
Open-Circuit Characteristics

- When saturation begins, occ bends over
- Higher field current results in less and less increase in generated voltage



Example: Saturation Effects

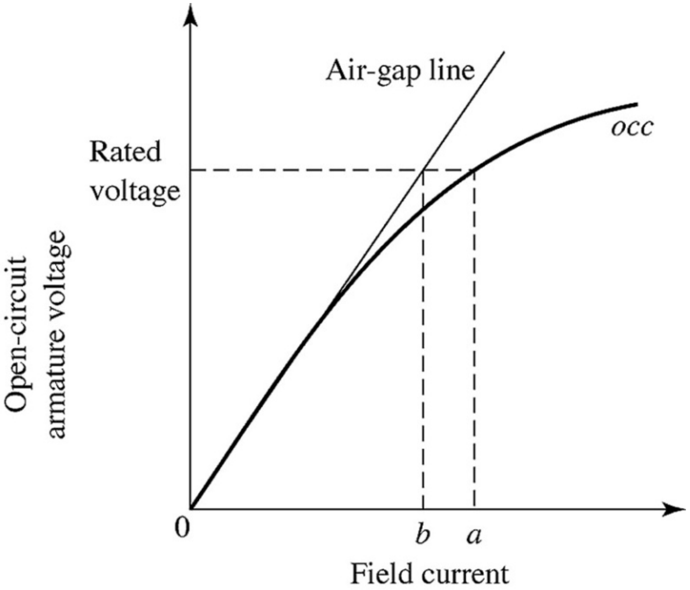
- *Fitzgerald*, Example 5.3
- Open-circuit test on a 3-phase, 60 Hz synchronous generator shows that the rated open circuit voltage of 13.8 kV is produced by a field current of 318 A. Extrapolation of the airgap line from a set of measurements shows that the field current corresponding to 13.8 kV on the airgap line is 263A. Find the saturated and unsaturated values of L_{af}.



Example: Saturation Effects

Remember that

$$L_{af} = \frac{\sqrt{2}E_{af}}{\omega_e I_f}$$



In the saturated case, E_{af}=13.8kV/$\sqrt{3}$ = 7.97 kV. The saturated value of L_{af} is:

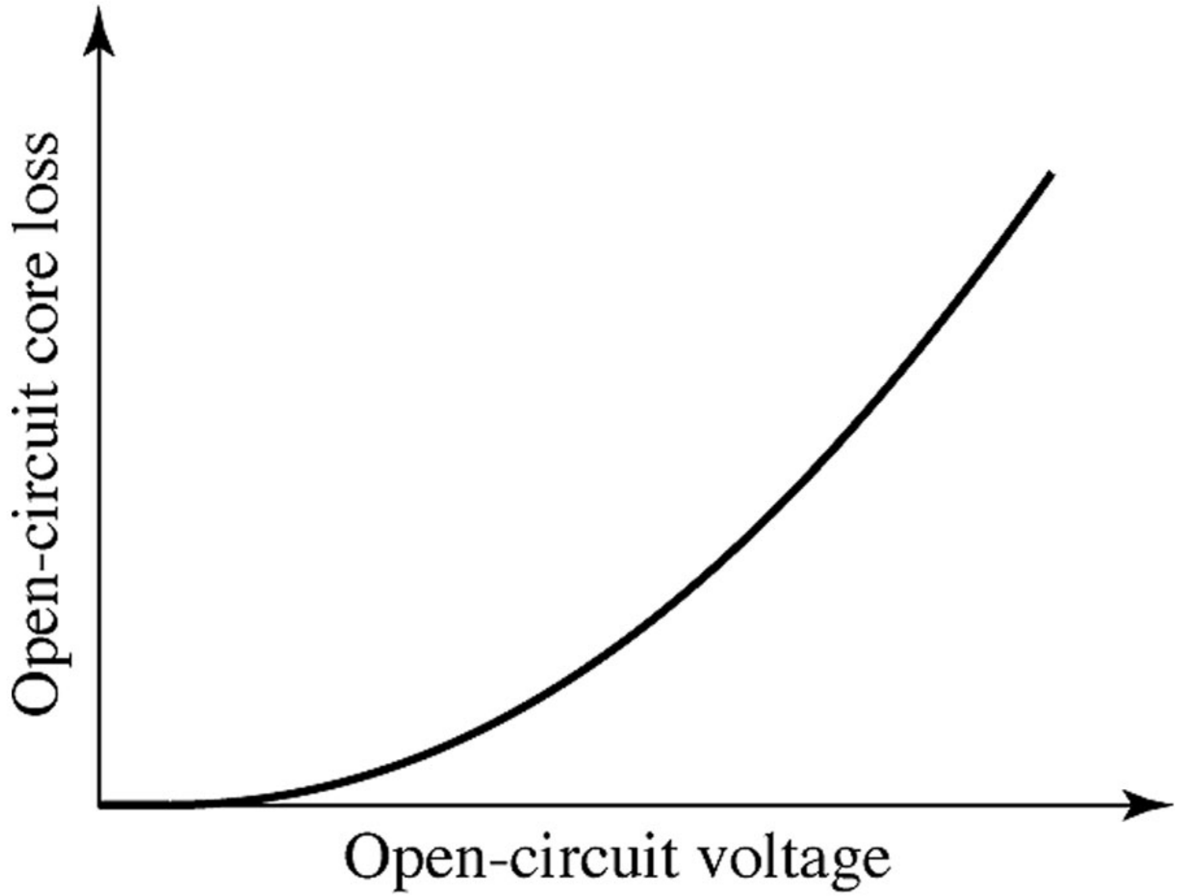
$$(L_{af})_{sat} = \frac{\sqrt{2}(7970)}{(2\pi \times 60)(318)} = 94\ mH$$

The unsaturated value of L_{af} is:

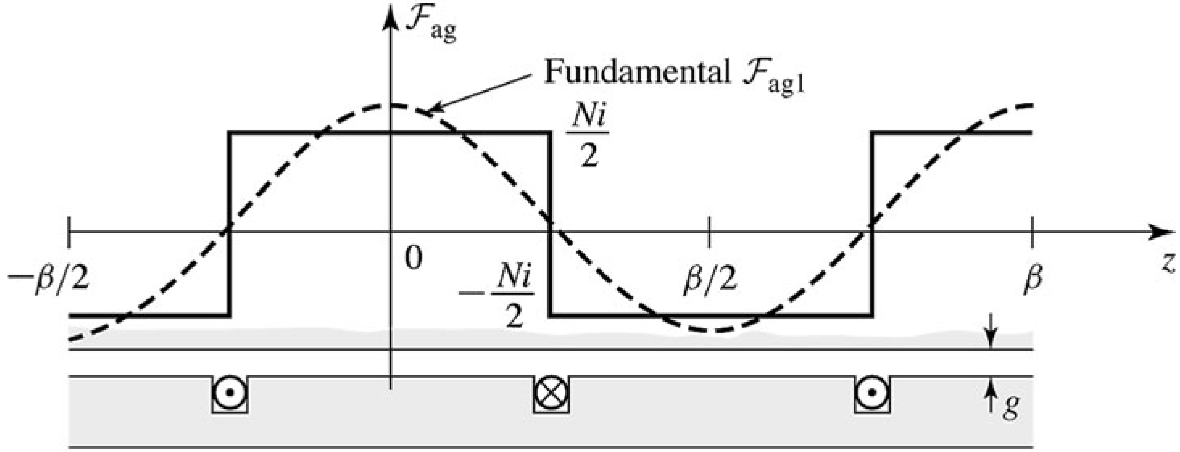
$$(L_{af})_{unsat} = \frac{\sqrt{2}(7970)}{(2\pi \times 60)(263)} = 114\ mH$$

Typical Open-Circuit Core Loss Curve

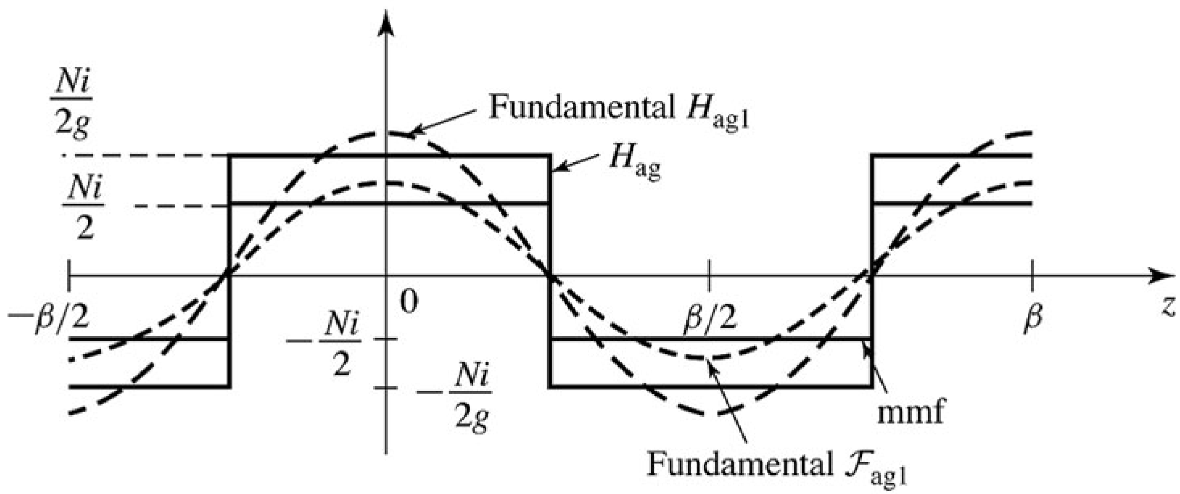
- Core loss due to eddy currents and hysteresis loss



Linear Machine



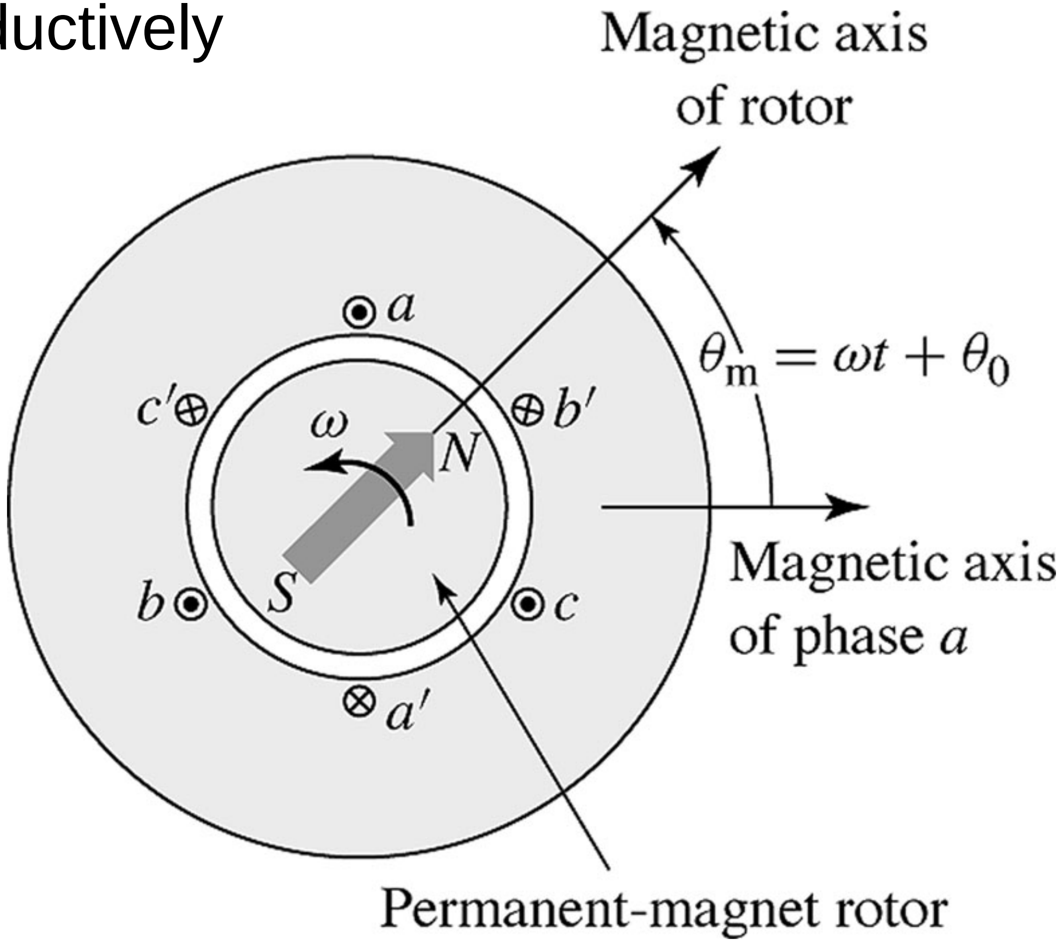
(a)



(b)

Permanent Magnet Synchronous Motor

• Rotating permanent magnet provides field flux
• Shaft position sensing can be done with Hall sensors, LEDs, or inductively



Permanent Magnet LSM

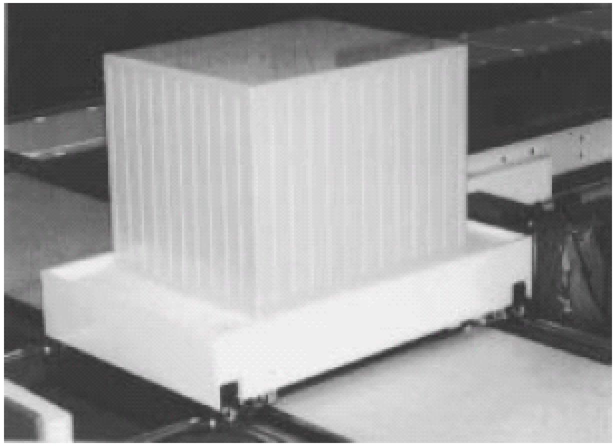
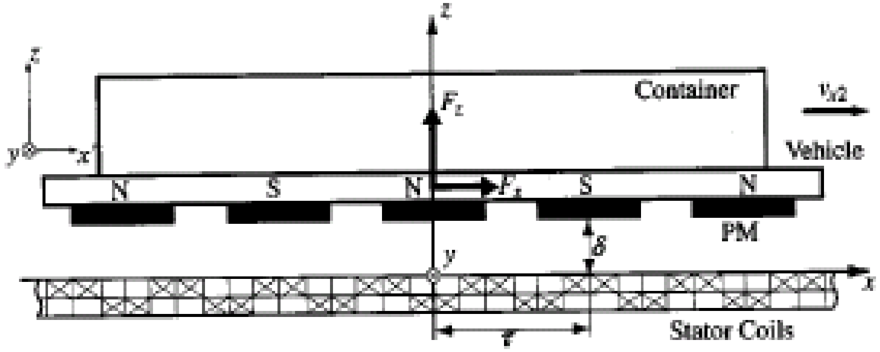


Fig. 1. PM LSM container test vehicle and its guideway.

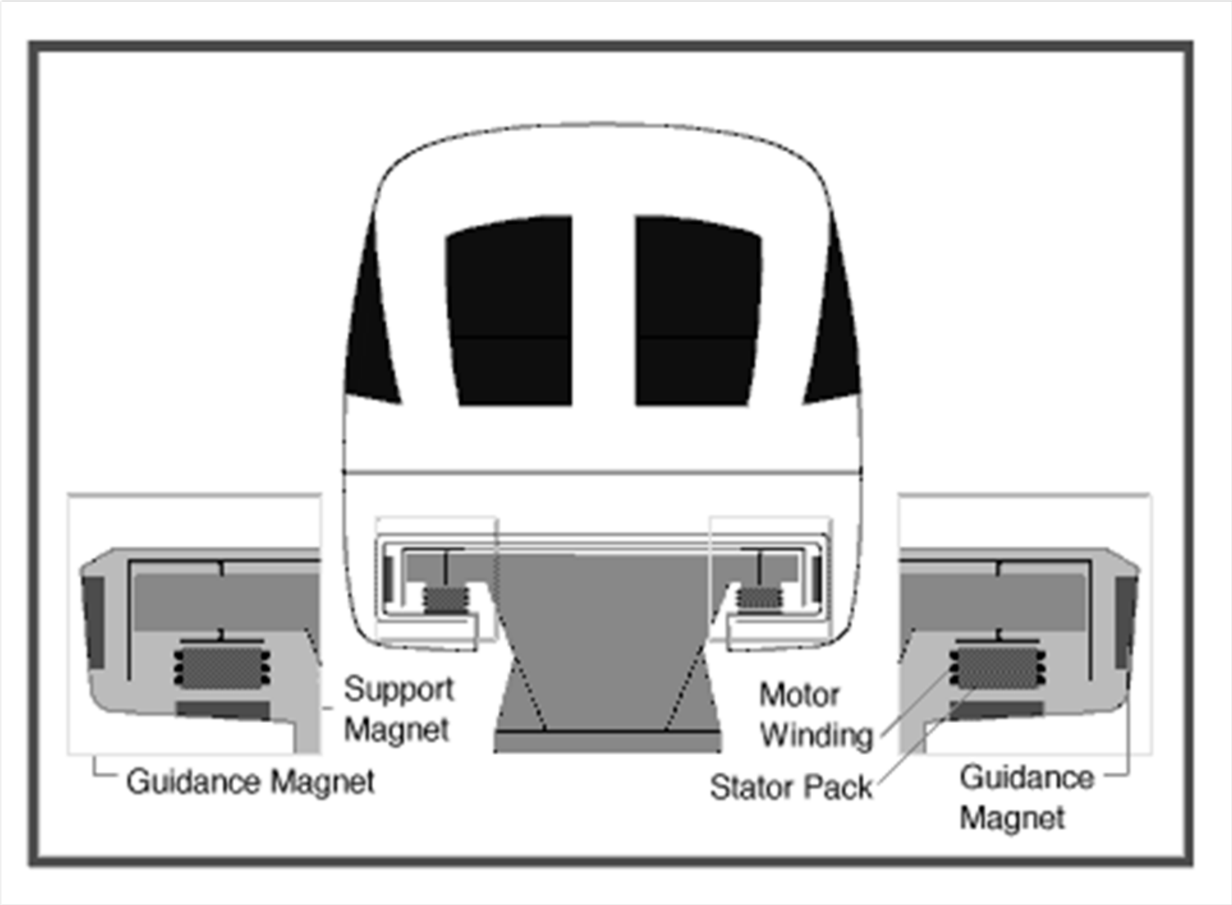


(a)

Reference: K. Yoshida, et. Al., “Mass Reduction and Propulsion Control for a Permanent-Magnet Linear Synchronous Motor Vehicle,” IEEE Transactions on Industry Applications, vol. 37, no. 1, January/February 2001, pp. 67-72

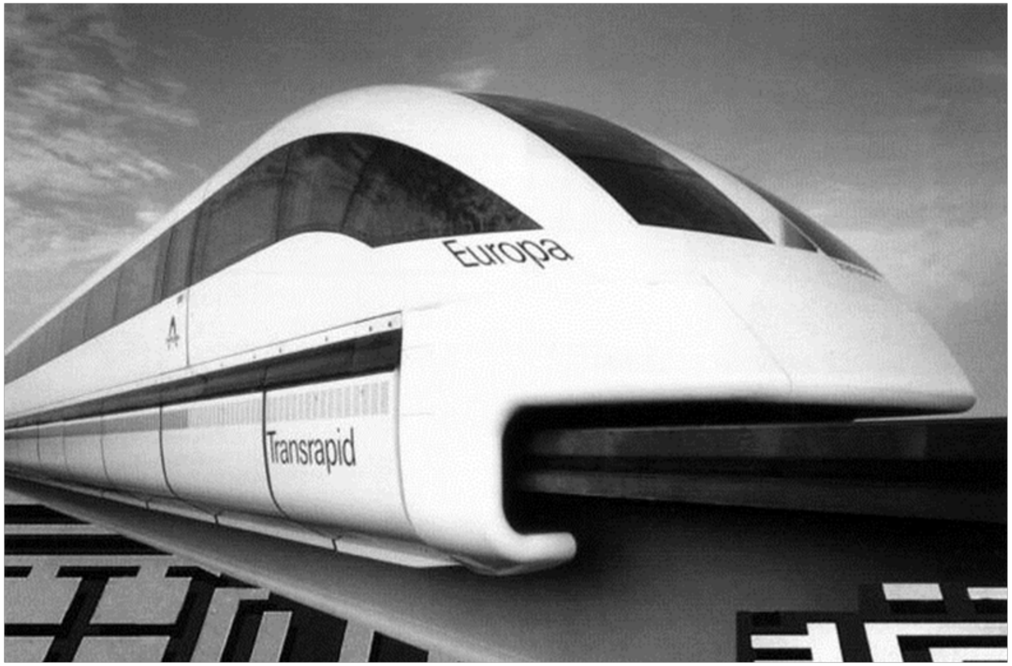
Electromagnetic Suspension --- Maglev

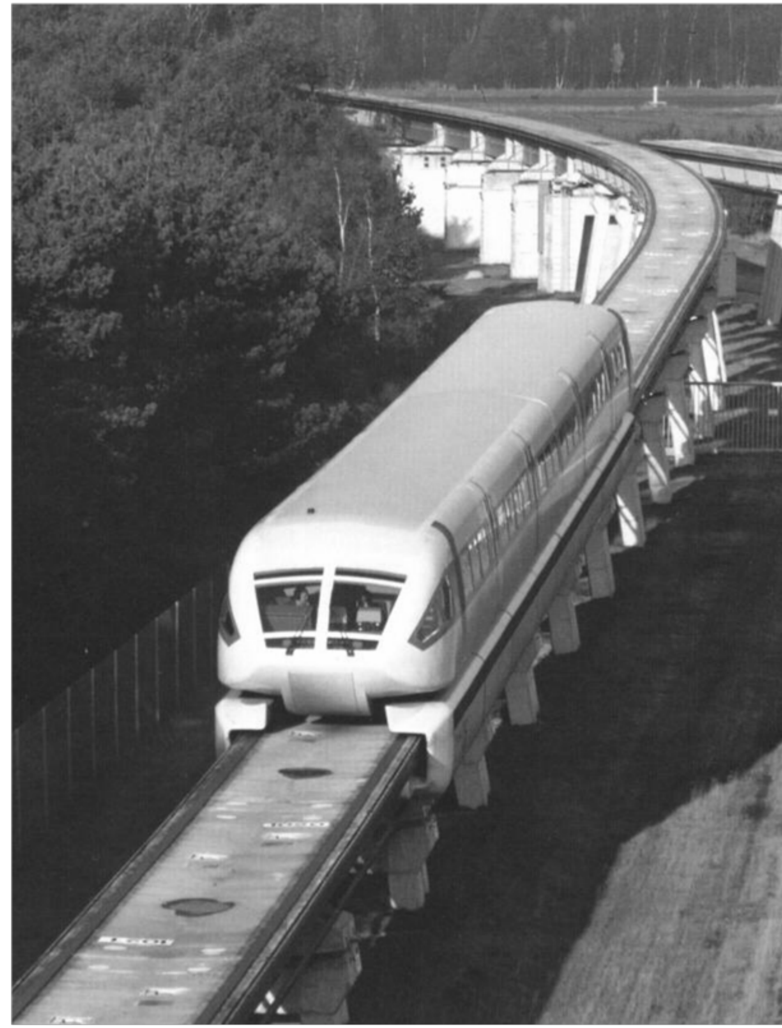
- LSMs or LIMs are used in Maglev



Maglev - German Transrapid

- Uses LSM

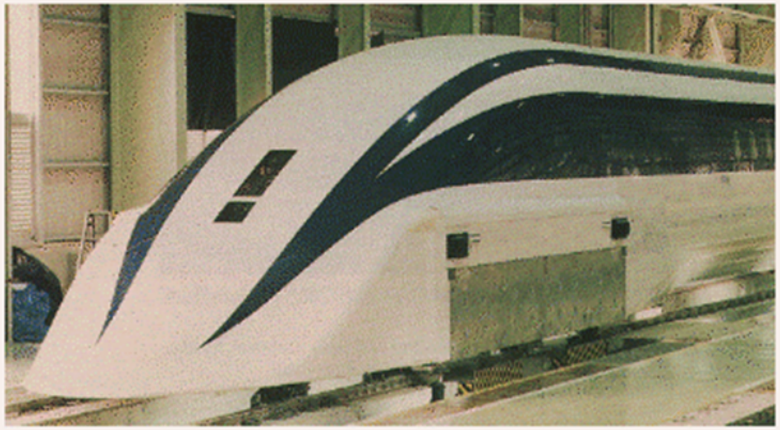




Maglev - Japanese EDS

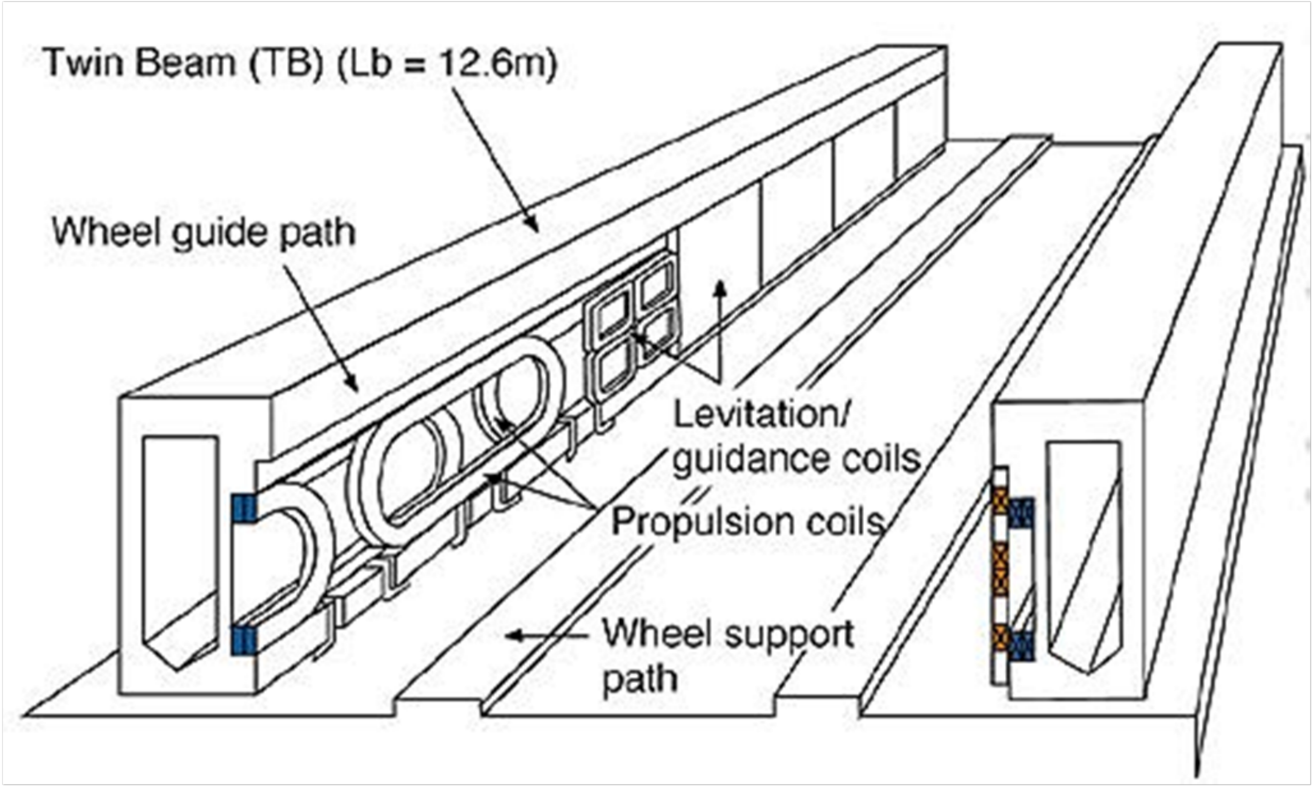
- Uses LSM


Aero-wedge Style


Double Cusp Style

Japanese EDS Guideway

- Shown are LSM propulsion coils, as well as levitation and guidance coils



Motor Power System

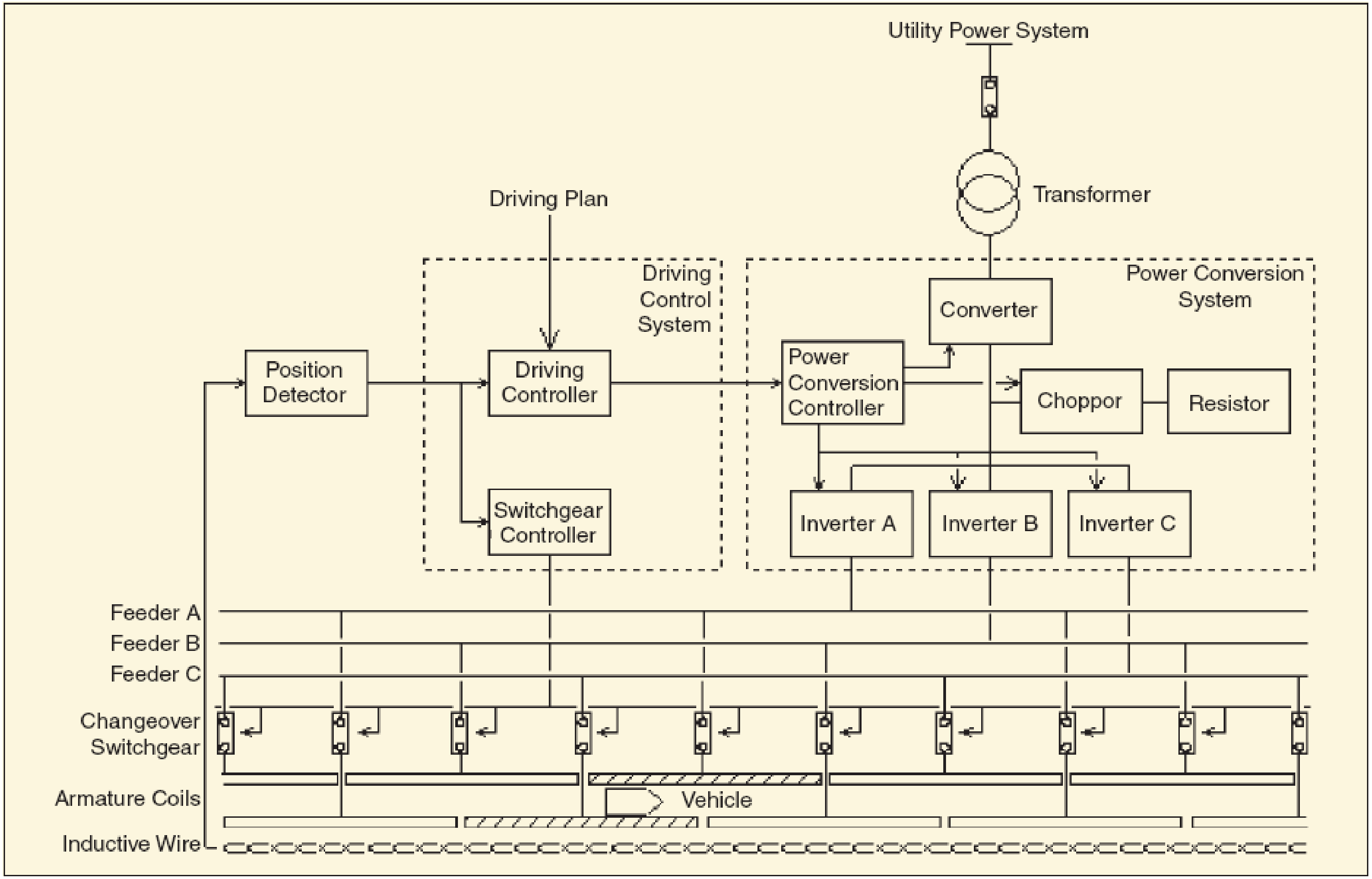
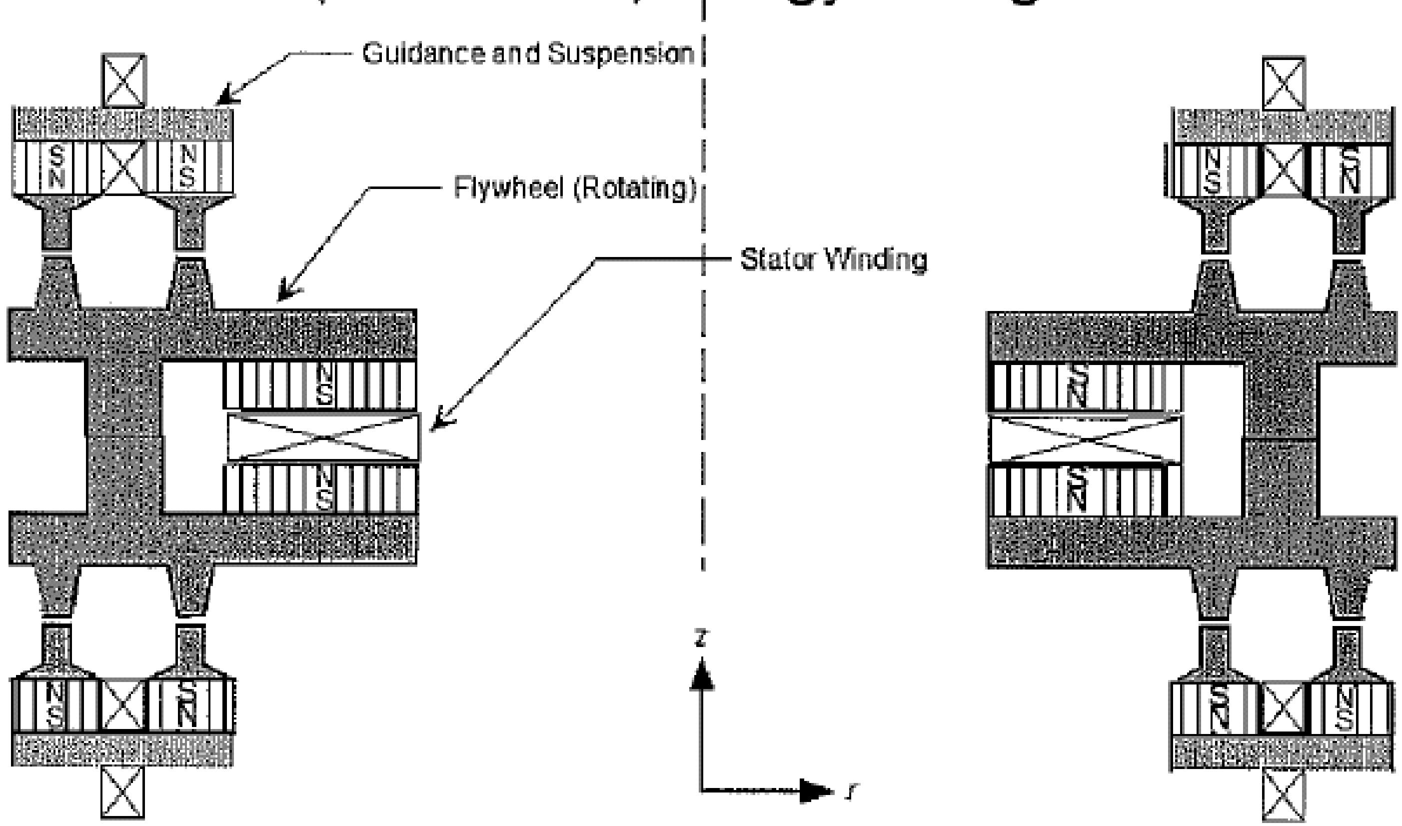


Fig. 7. Power supply system for the Yamanashi Maglev test line.

Reference: M. Ono, et. al., "Japan's Superconducting Maglev Train," *IEEE Instrumentation and Measurement Magazine*, March 2002, pp. 9-15

NASA Flywheel with Synchronous PM Motor-Generator

- For NASA; P = 100W, energy storage = 100 W-hrs



Typical Motor Drive Configuration

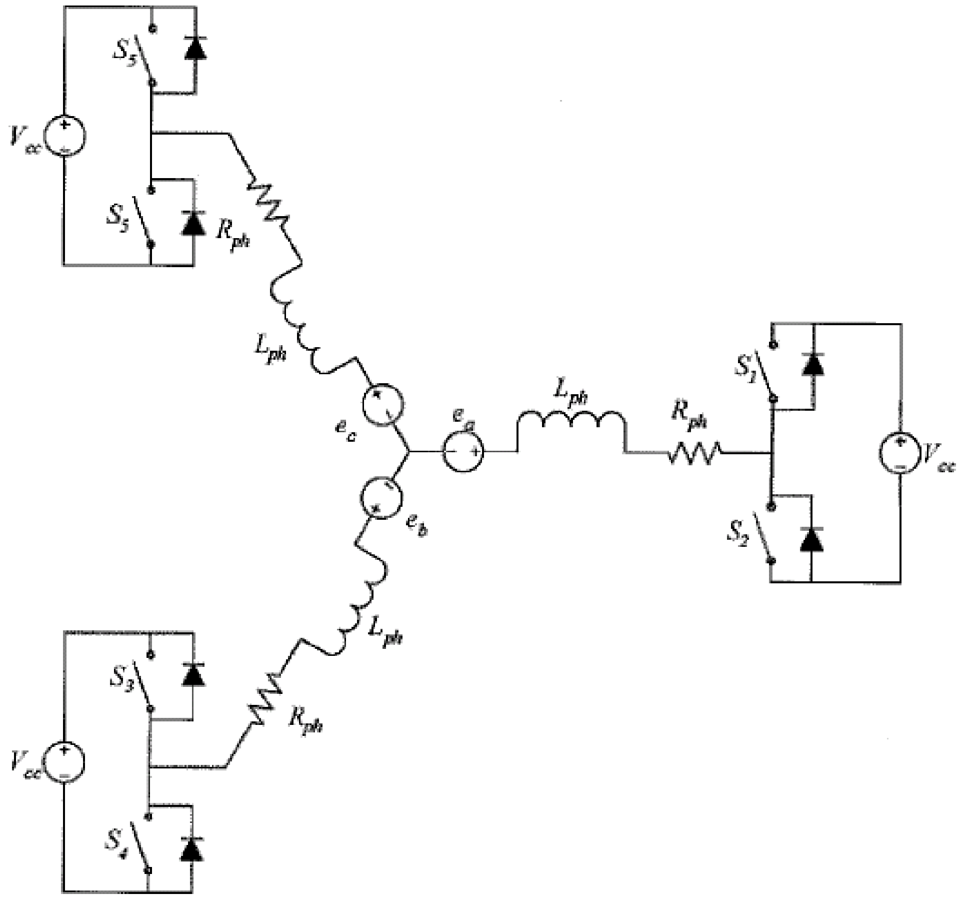
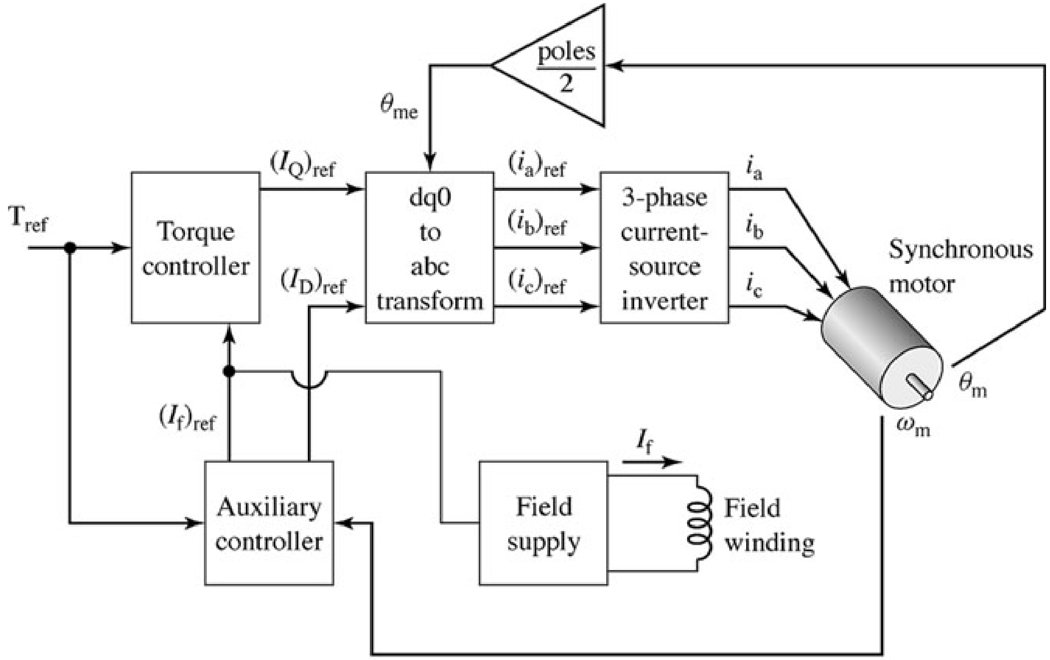


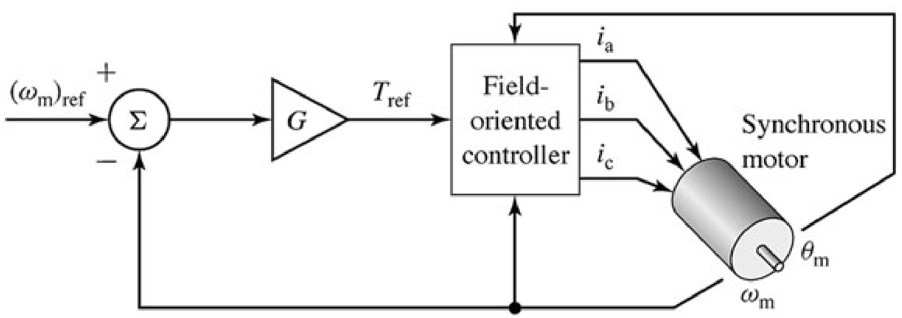
Figure 8-6. Y-connection configuration.

Reference: D. Hanselman, *Permanent Magnet Motor Design*, 2d edition,

Torque or Speed Control



(a)



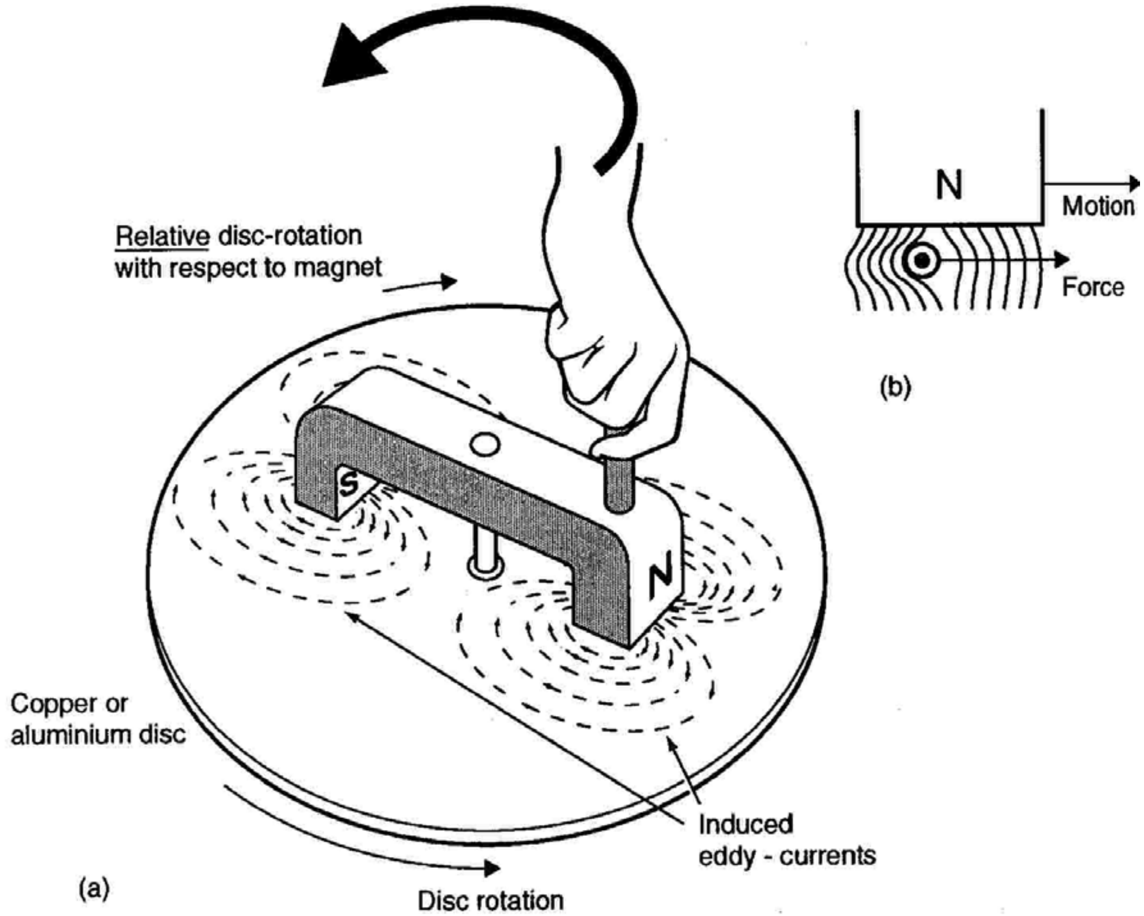
(b)

Induction Machines --- Overview

- An induction machine includes an excited stator (with rotating magnetic field)
- This rotating magnetic field induces currents in a shorted-turn rotor
- **B** (magnetic flux density, Tesla) and **J** (current density, A/m^2) create forces on the rotor, inducing motion
- Most induction machines are motors, not generators
- Some induction generators are used in wind power

Intuitive Induction Motor

- Note that disk rotation occurs at speed lower than rotation speed of magnetic field



Reference: Irving Gottlieb, *Practical Electric Motor Handbook*, Newnes, 1997, pp. 64

Brief History

- 7 patents filed in 1887 by Tesla covering generators, transformers, transmission lines, the polyphase system, etc.
- Tesla’s patents were bought by George Westinghouse
- Westinghouse produces practical induction motor in 1892
- 1891---Thomson-Houston company begins work on 3-phase induction machines
- 1895---development of the “squirrel cage”
- 1896 --- GE and Westinghouse cross-license; Steinmetz at GE

Brief History

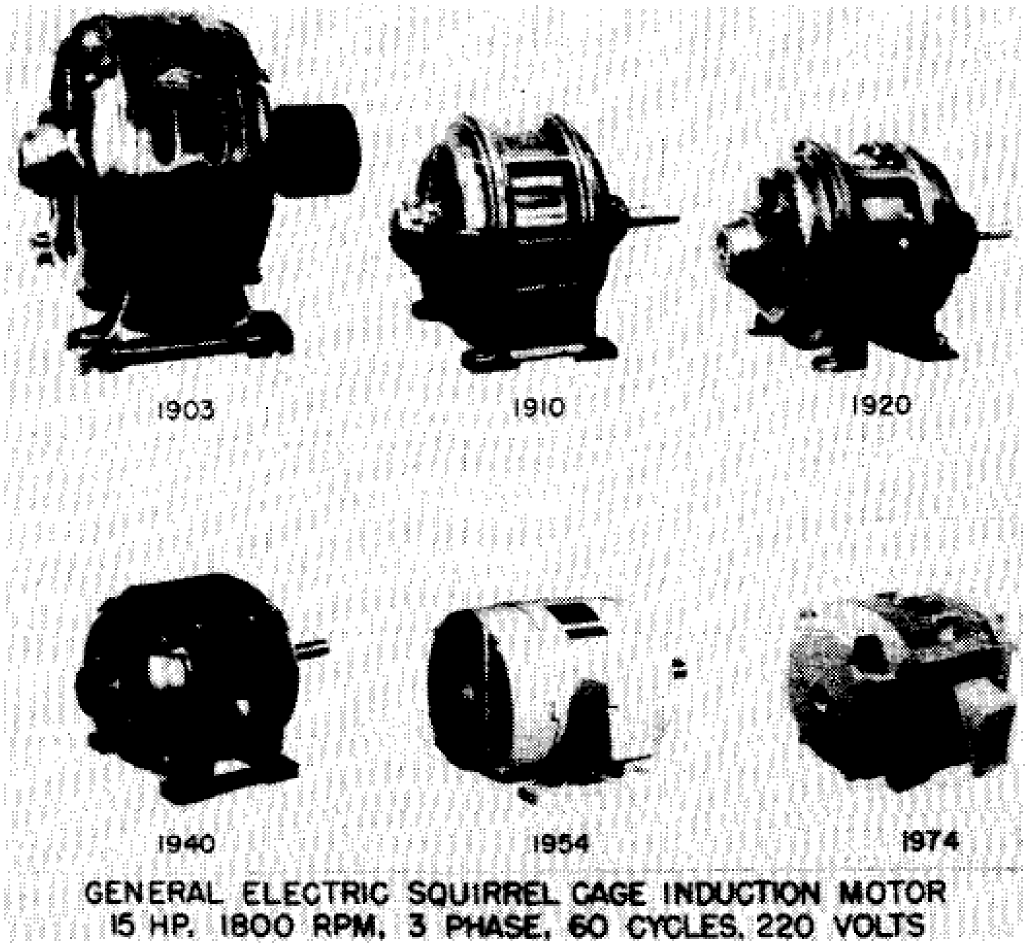


Fig. 2. Successive versions of the induction motor, 1897–present.

Reference: P. Alger and R. Arnold, "The History of Induction Motors in America," *Proceedings of the IEEE*, vol. 64, no. 9, September 1976, pp. 1380-1386

Brief History

TABLE I

Years	Horsepower Rating	Temperature Rise
1898–1903	7.5	40°C by thermometer
1903–1905	10	"
1905–1914	15	"
1914–1924	20	"
1924–1929	25	"
1929–1940	30	"
1940–1956	40	50°C by resistance
1956–1961	50	"
1961–1966	60	"
1966–	100	80°C by resistance

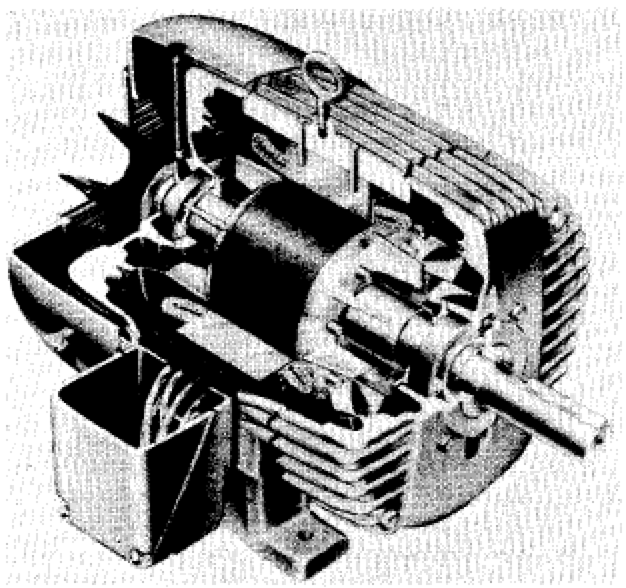


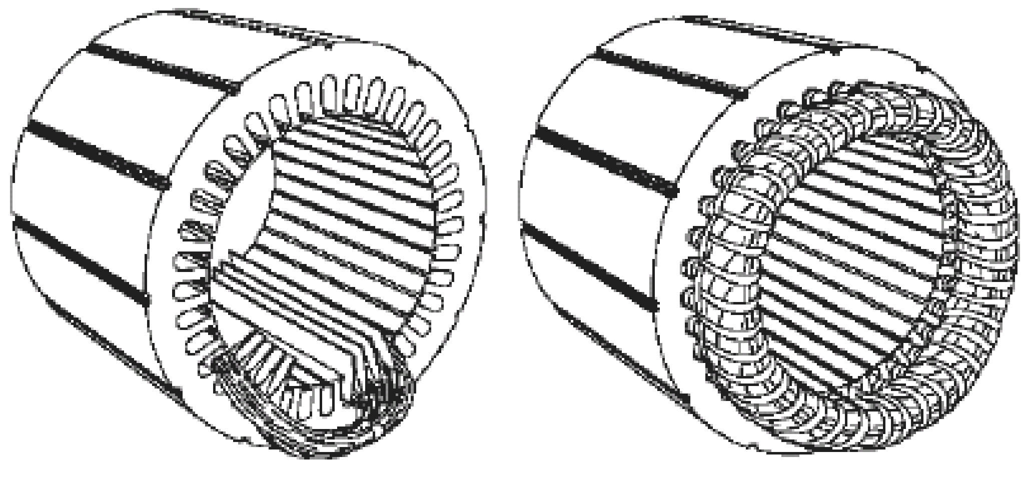
Fig. 3. Exploded view of modern induction motor.

Reference: P. Alger and R. Arnold, "The History of Induction Motors in America," *Proceedings of the IEEE*, vol. 64, no. 9, September 1976, pp. 1380-1386

Stator Windings

- Produces traveling wave

FIGURE 1: A TYPICAL STATOR



Reference: Microchip, Inc., Application Note AN887

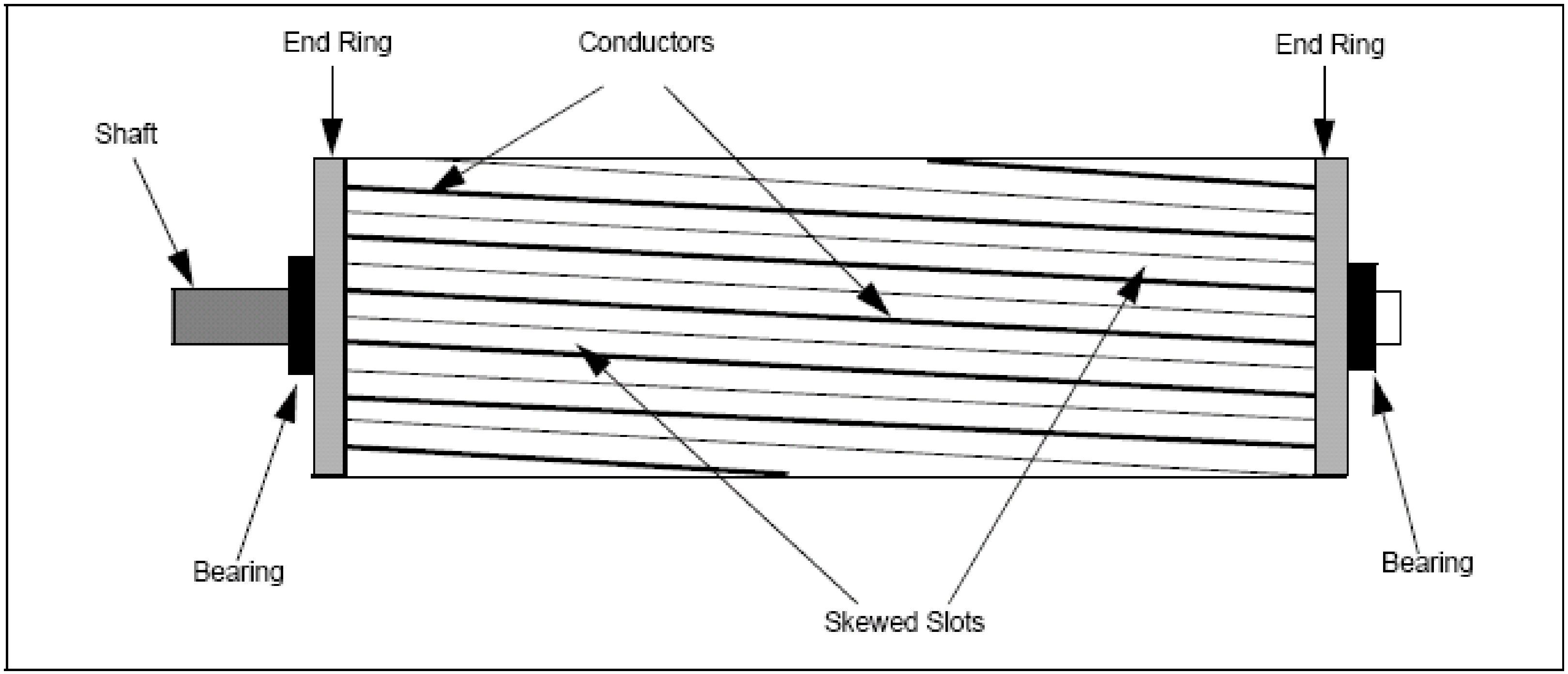
Some Issues in Induction Motor Construction

- Stator and rotor are made of steel laminations, fractions of a millimeter thick
- Stator and rotor with windings are immersed in varnish to provide insulation. The magnet wire has an insulation class as well
- Rotor shaft made of forged steel
- Before final assembly, rotor is dynamically balanced

“Squirrel Cage” Rotor

- Reacts to the traveling wave produced by the stator winding

FIGURE 2: A TYPICAL SQUIRREL CAGE ROTOR



Reference: Microchip, Inc., Application Note AN887

Basic Induction Machines

- We will model an induction machine as a transformer
- AC current is applied to stator; AC current induced in rotor
- Rotor turns at n RPM
- Synchronous speed of stator field is n_s RPM
- $n < n_s$
- Difference between synchronous speed and rotor speed is "slip"; $s = (n_s – n)/n_s$
- Rotor speed $n = (1\text{-}s)n_s$
- Mechanical speed related to synchronous angular velocity by $\omega_m = (1\text{-}s)\omega_s$
- Relative motion between stator and rotor field induces slip frequency $f_r = sf_e$ in rotor

Basic Induction Machines

- Electrical behavior of an induction machine is similar to a transformer, with the additional feature of a frequency transformation

“Slip”

- Slip is an indication of how close to the speed of the rotating magnetic field the rotor speed is.
- (Rotor speed is always less than speed of the rotating magnetic field)
- The slip is called “s” and $0 < s < 1$
- The rotor speed is “s” % of the synchronous speed
- The frequency of the induced currents in the rotor is:

$$f_r = sf_e$$

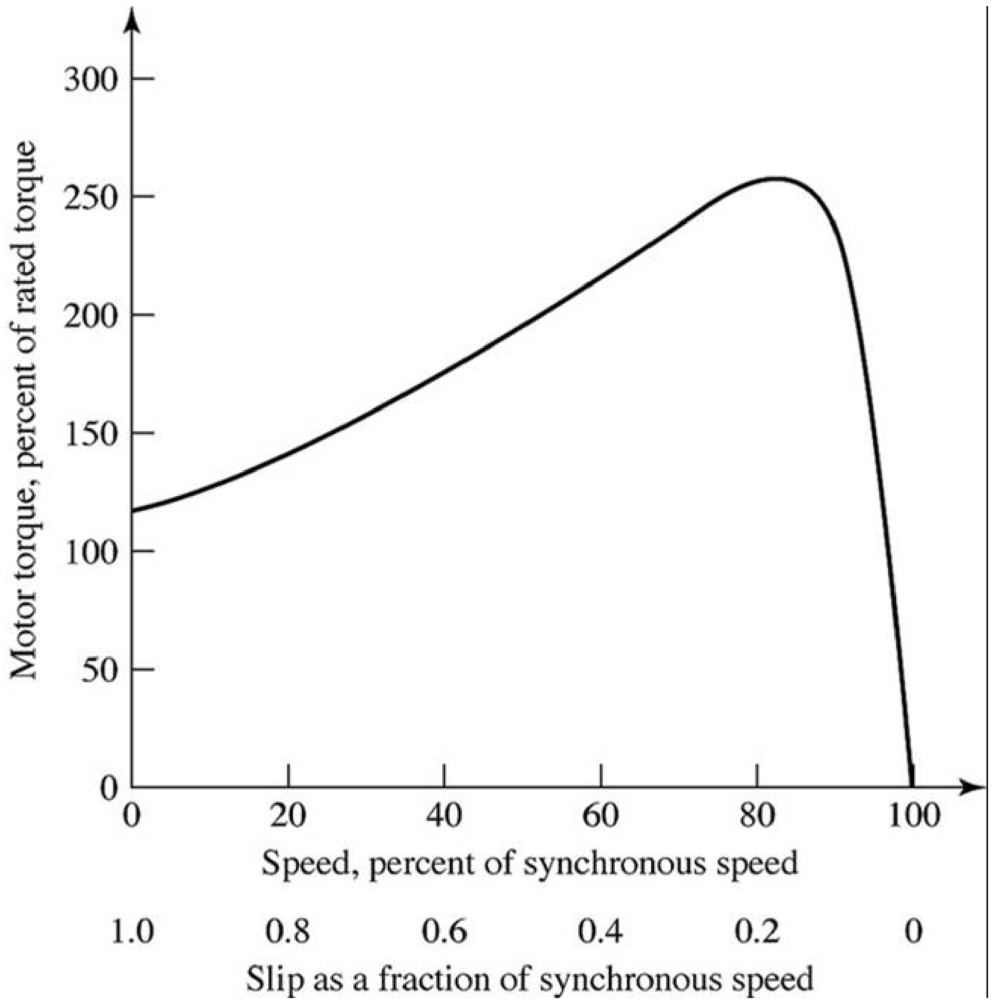
f_r = rotor frequency
f_e = electrical frequency on stator

Starting and Running

- At start, rotor is stationary (n = 0) and slip is unity (s = 1). Rotor frequency f_r equals stator frequency f_e
- If torque is sufficient to overcome friction, motor starts and settles to operating speed < f_e
- Typically, slip s < 10%
- Rotor frequency $f_r = sf_e \approx$ 1-6 Hz in 60 Hz motor
- Rotor induced voltage is proportional to slip
- Rotor impedance is mostly resistive at low slip, so rotor current is also proportional to slip
- So, torque is proportional to slip at low slip
- As slip increases, rotor impedance increases and then rotor current is less-than-proportional to slip. Torque peaks.

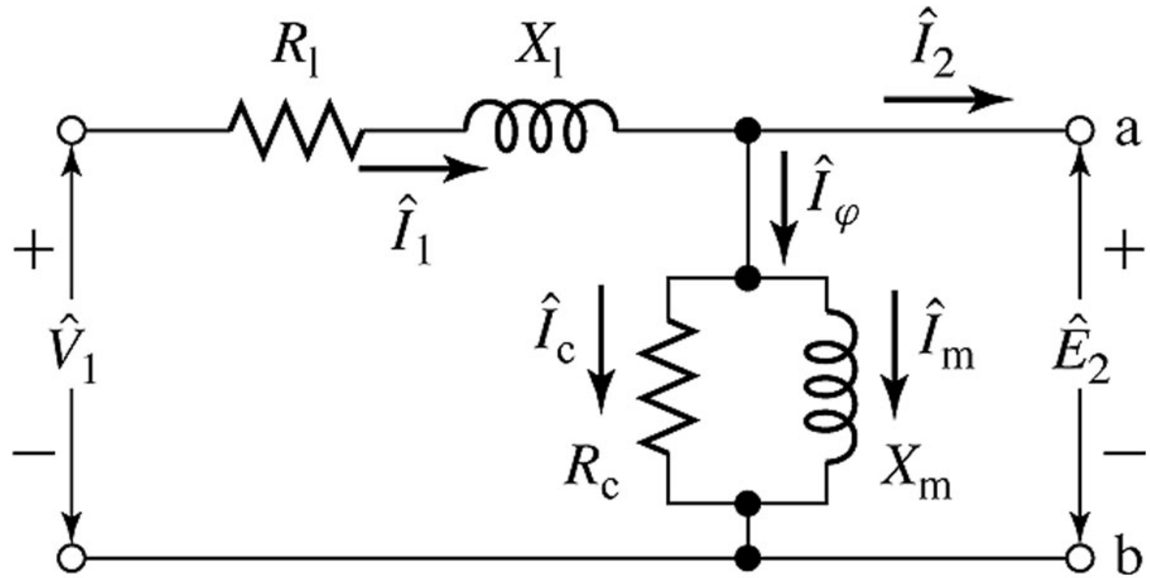
Torque-Speed Curve

- For constant voltage, constant frequency operation



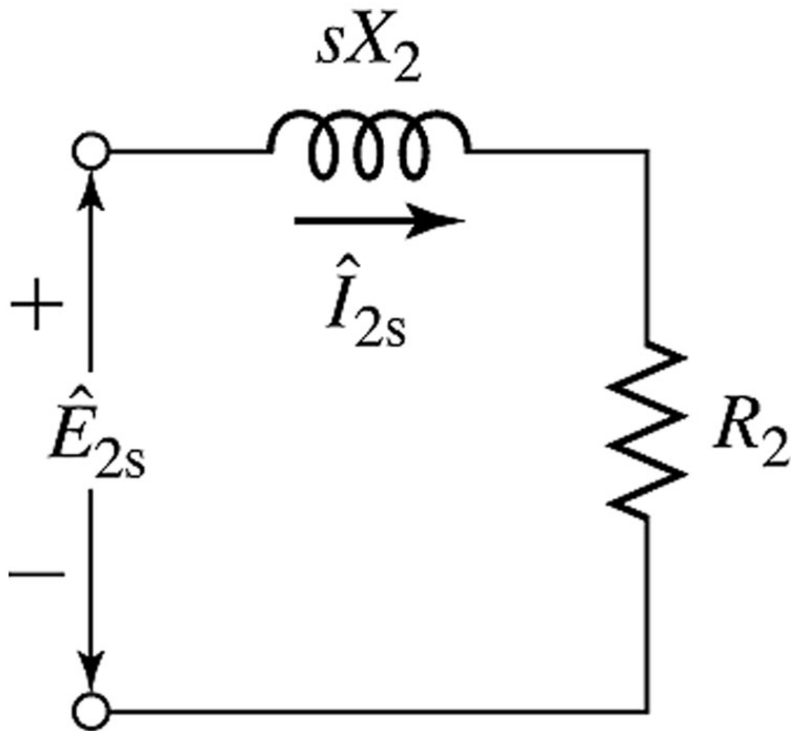
Stator Equivalent Circuit Per Phase

- Assuming symmetric polyphase winding and excitation voltage
- I_φ excites the stator
- I_2 is induced rotor current
  - R_1 = winding resistance. X_l = stator leakage reactance
  - R_c = core loss resistance. X_m = core excitation reactance



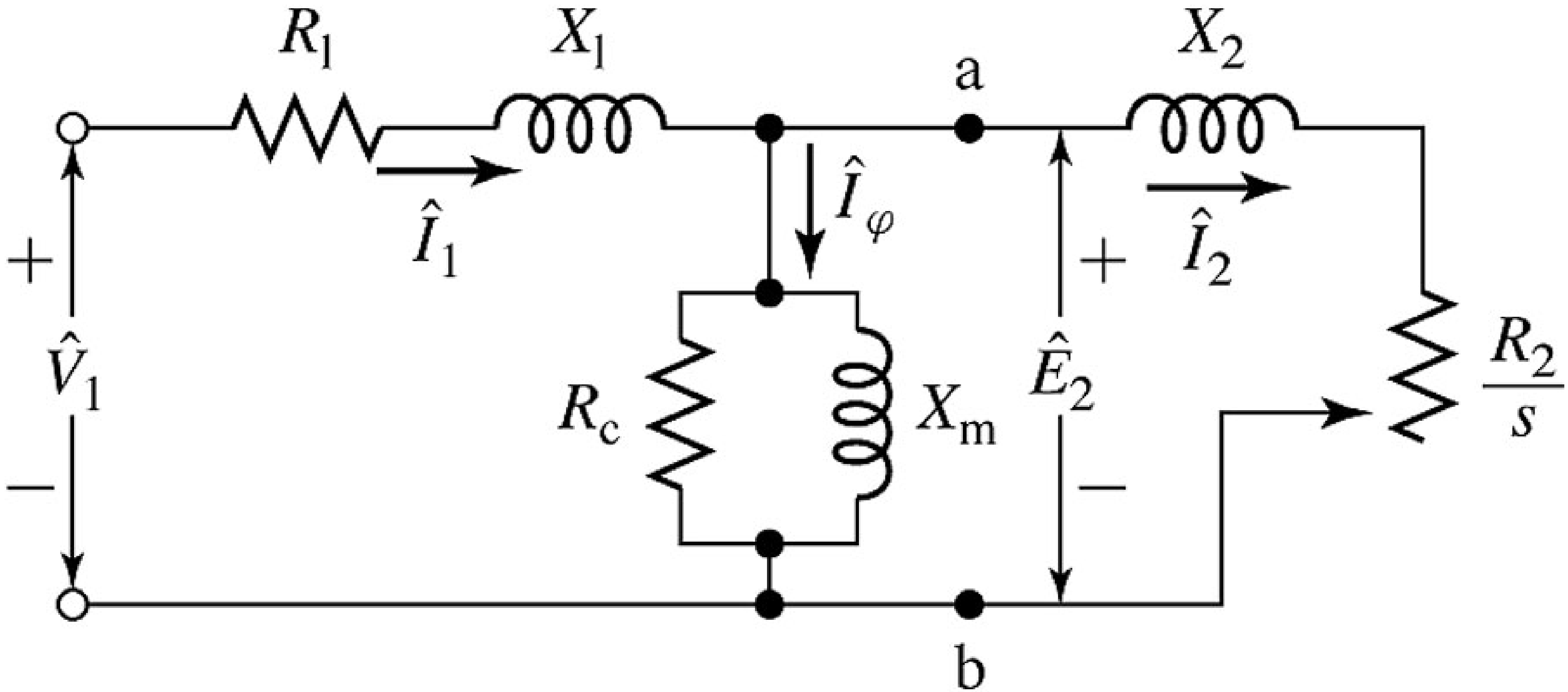
Rotor Equivalent Circuit at Slip

- I_φ excites the stator
- I_2 is rotor current
- Note that the rotor reactance is scaled by “s” since there is a change of frequency from stator to rotor



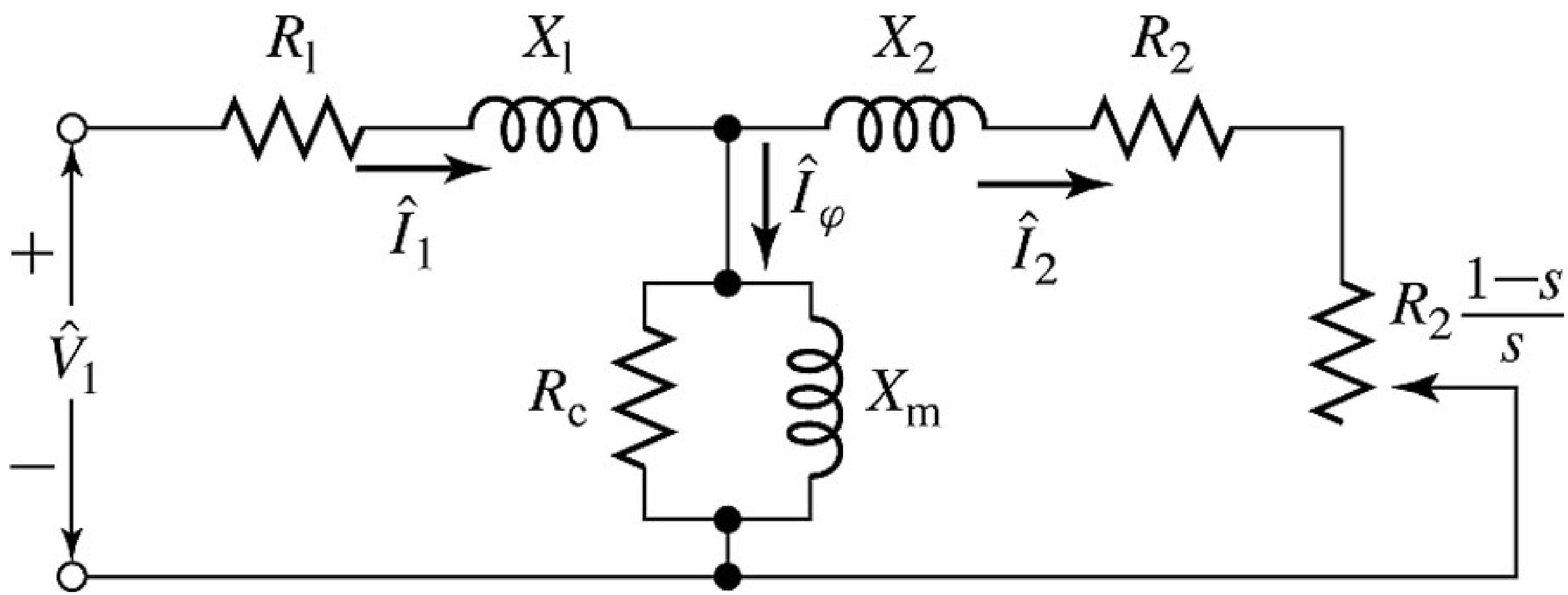
Single Phase Equivalent Circuit

- Note that the rotor resistance (R_2/s) varies as the motor speed varies



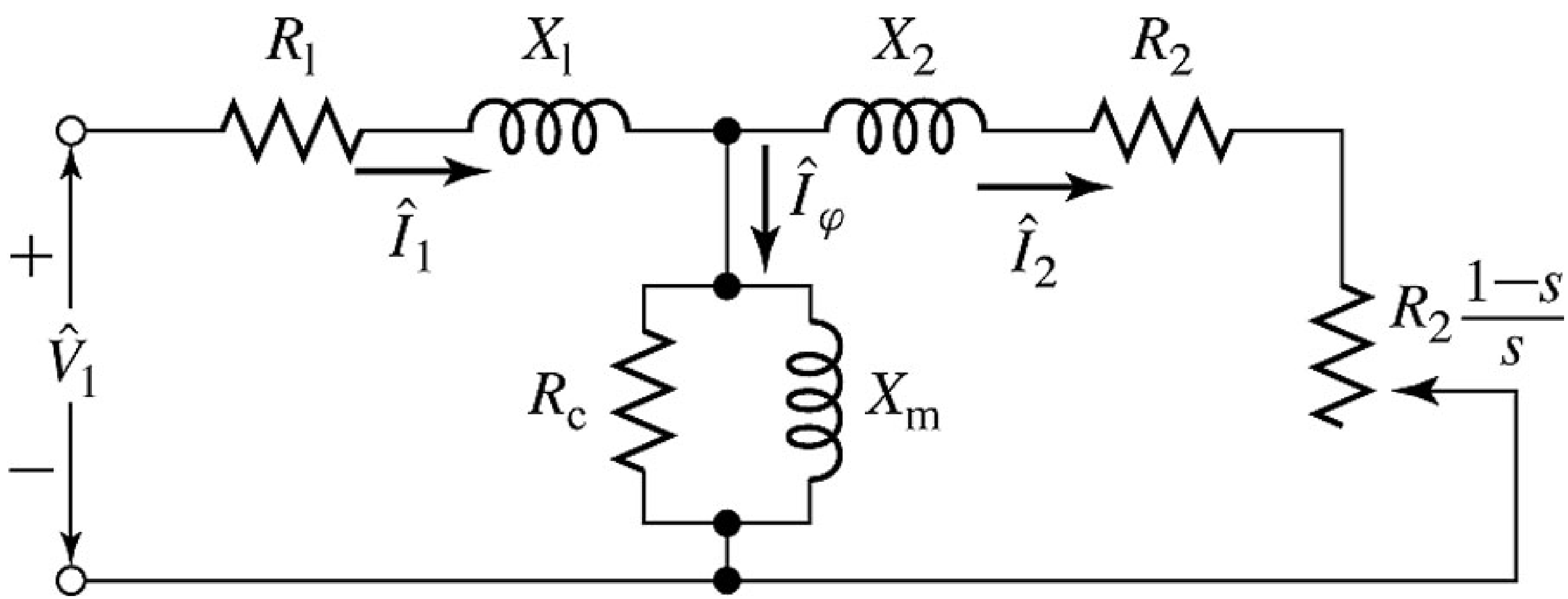
Single Phase Equivalent Circuit (Alternate Form)

- R_2 contributes to rotor loss.
- $R_2(1\text{-}s)/s$ is the mechanical power output component
- Power P_{gap} is sent across the airgap. Some is dissipated as rotor loss; some goes into mechanical power output

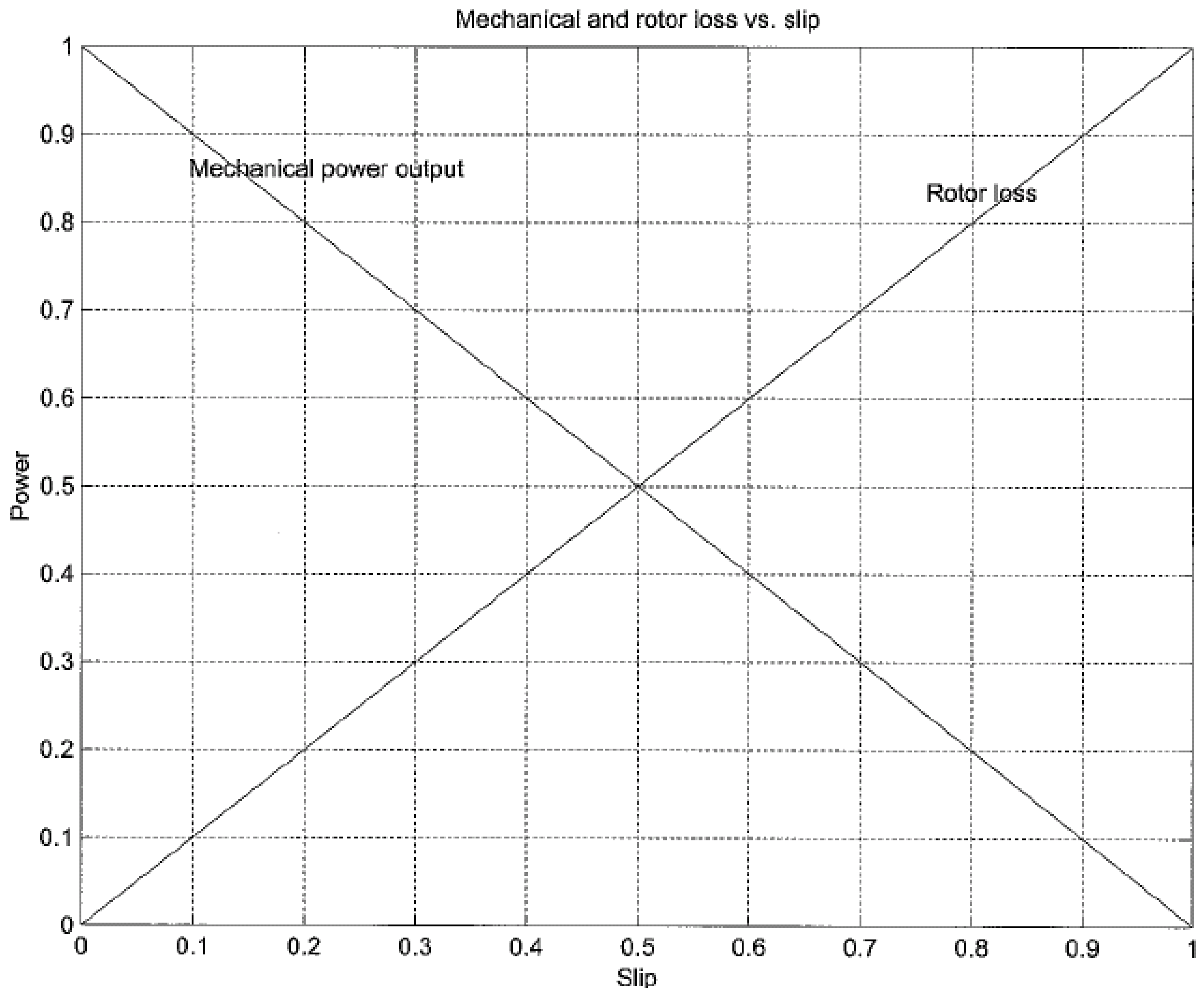


Rotor Loss and Mechanical Power

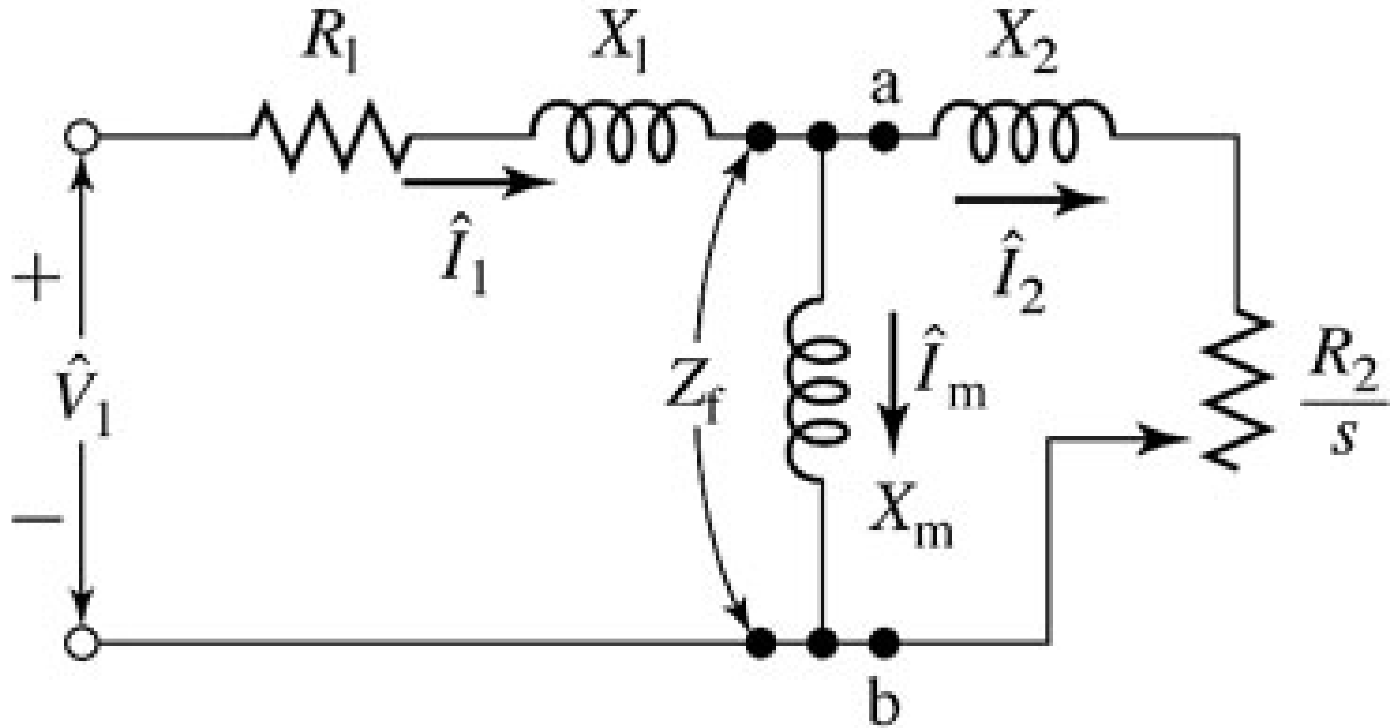
- $P_{mech} = (1\text{-}s)P_{gap}$
- $P_{rotor} = sP_{gap}$
- Fraction (1-s) of gap power is converted to mechanical power; fraction s is converted to heat in the rotor
- An induction motor operating at high slip is very inefficient



Rotor Loss vs. Slip

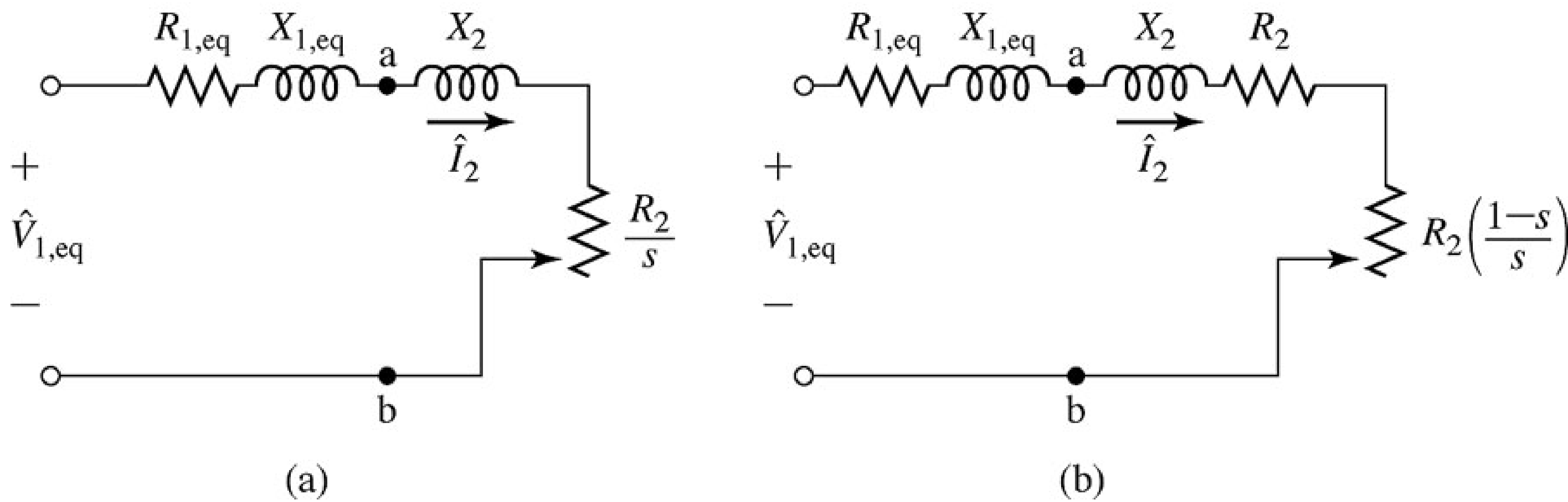


Single Phase Equivalent, Ignoring Core Loss

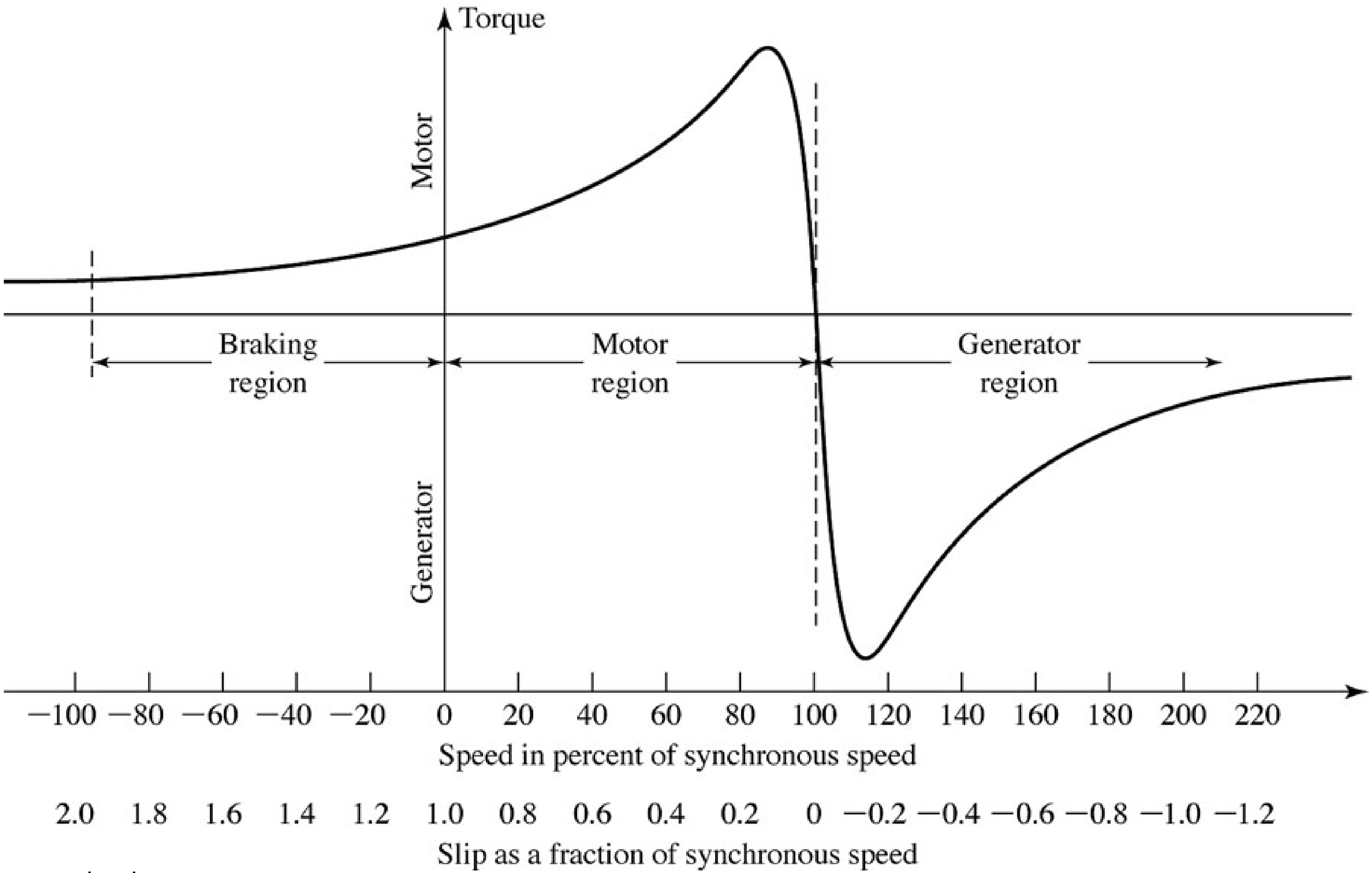


(a)

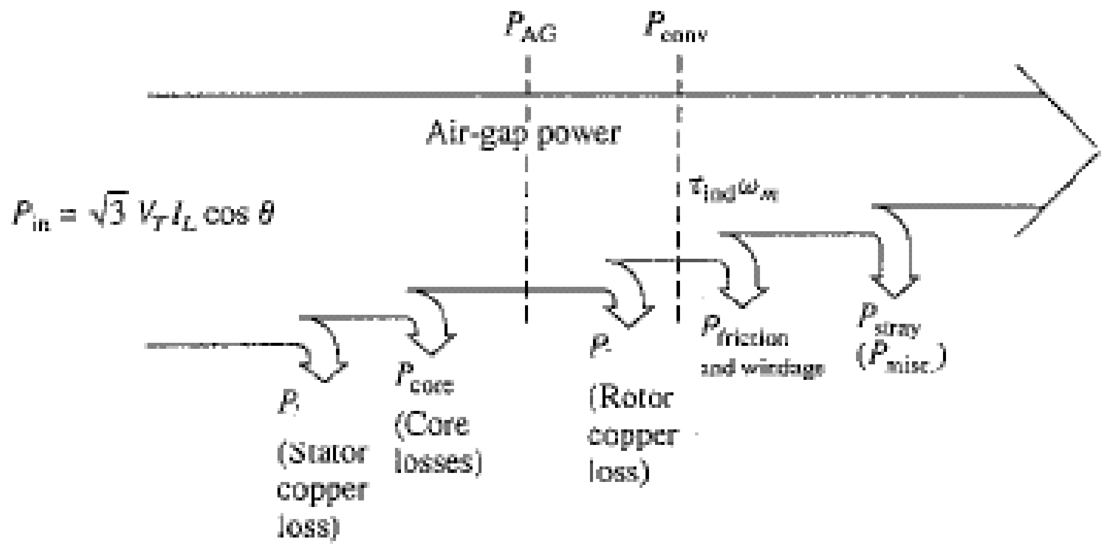
Thevenin Equivalent



Braking/Motor/Generator Curve



Power Flow in an Induction Motor



P_{IN} = 3 phase power

P_{stator} = I^2R loss in stator

P_{core}: Eddy current and hysteresis loss

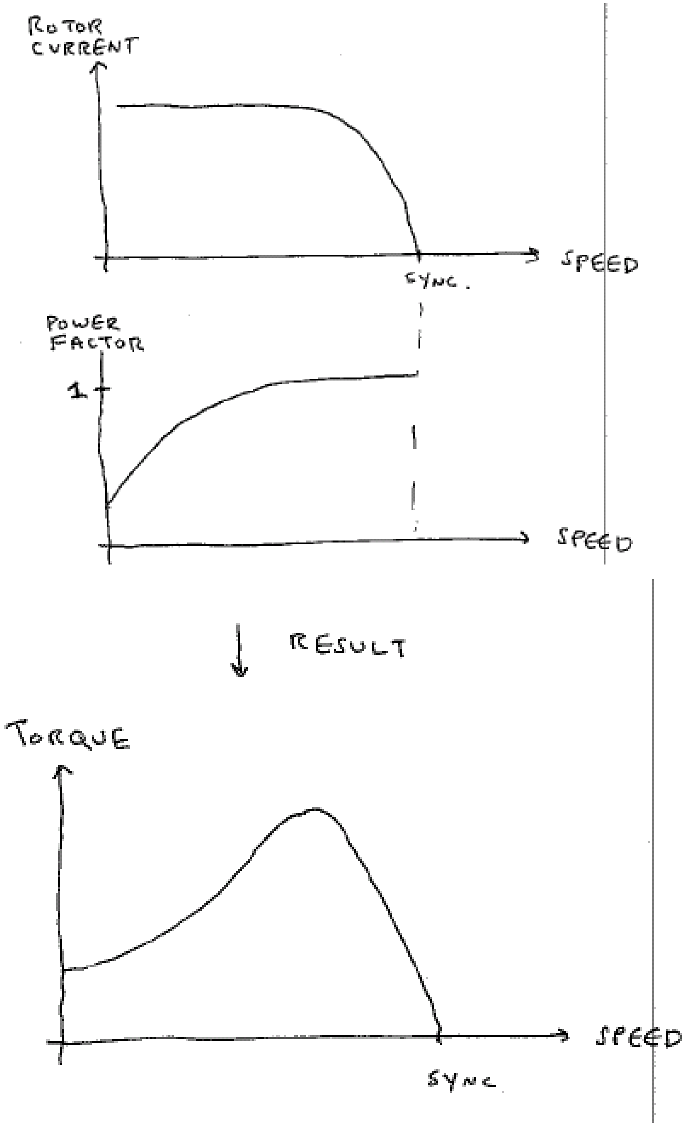
P_{AG}: Power transmitted across airgap

P_{rotor}: I^2R loss in rotor

Miscellaneous losses due to friction and windage

$P_{out} = T_{mech}\omega_m$

Graphical Development of Torque-Speed Curve



Locked-Rotor Current

TABLE 13–1
Table 430.7(B) Locked-Rotor Indicating Code Letters

Code Letter	Kilovolt-Amperes per Horsepower with Locked Rotor
A	0–3.14
B	3.15–3.54
C	3.55–3.99
D	4.0–4.49
E	4.5–4.99
F	5.0–5.59
G	5.6–6.29
H	6.3–7.09
J	7.1–7.99
K	8.0–8.99
L	9.0–9.99
M	10.0–11.19
N	11.2–12.49
P	12.5–13.99
R	14.0–15.99
S	16.0–17.99
T	18.0–19.99
U	20.0–22.39
V	22.4 and up

Power Quality and Effect of Motor Starting

- During startup, very large currents can be drawn (typically 5-10$\times$ of full-load current)
- This can cause line voltage to sag

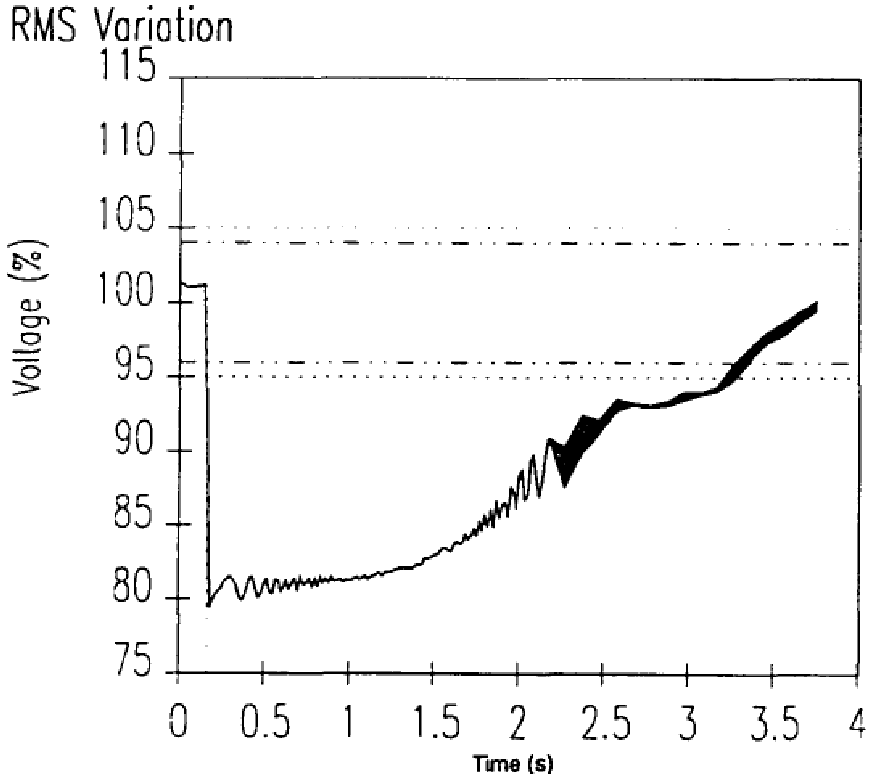
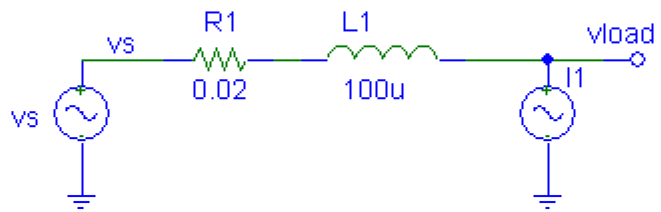


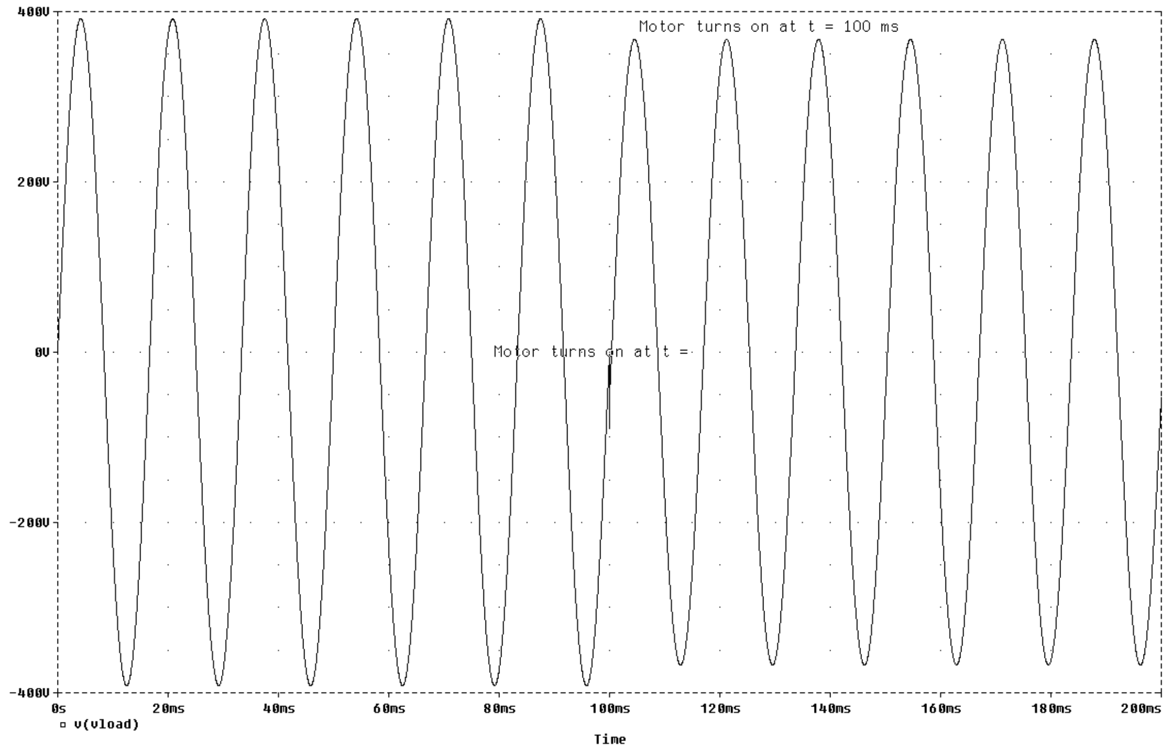
Figure 7—Temporary voltage sag caused by motor starting

Reference: IEEE Std. 1159-1995, pp. 18

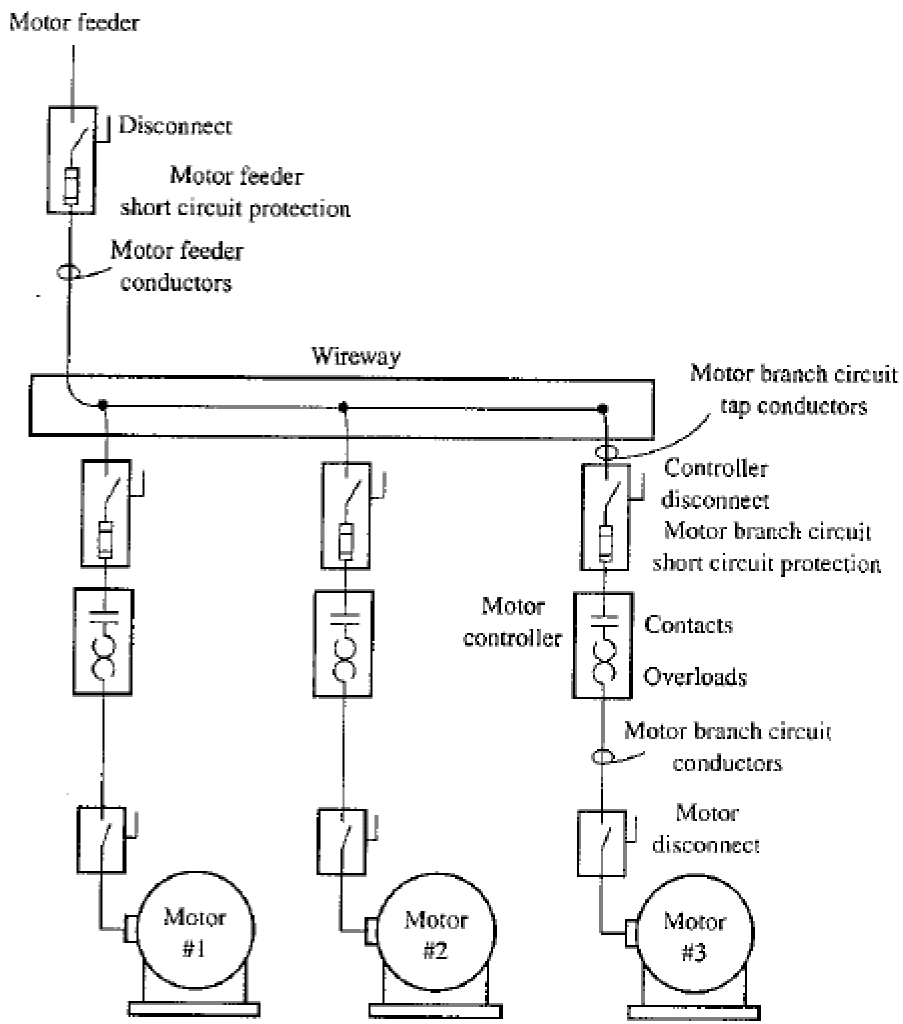
Example: Motor Starting

- 277V line-neutral, and motor startup current of 1000A

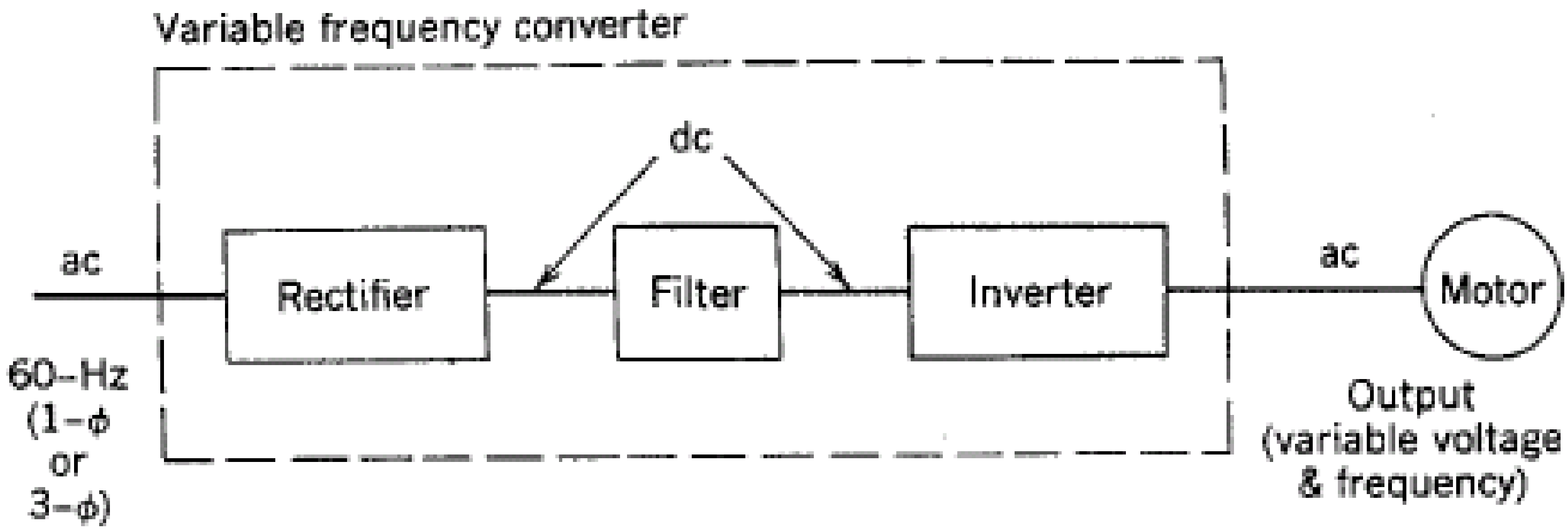




Typical Multiple-Motor Installation and Protection



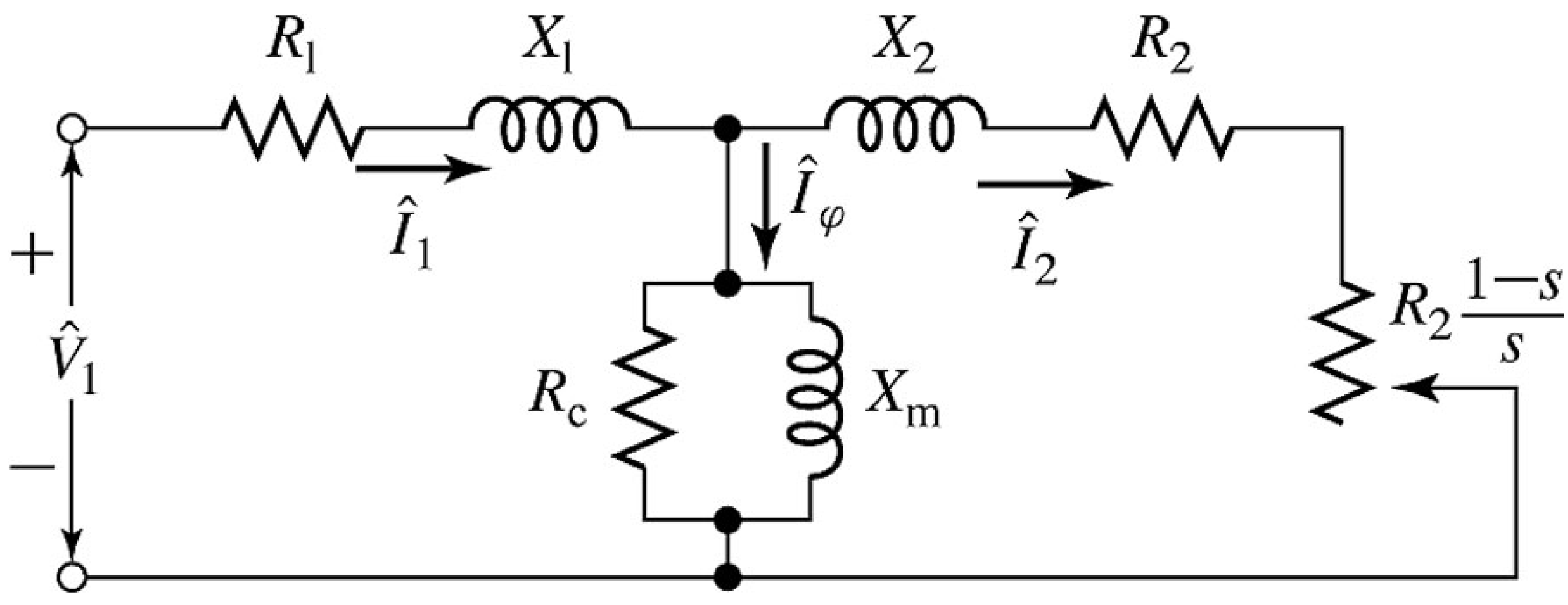
Typical Variable Frequency Drive



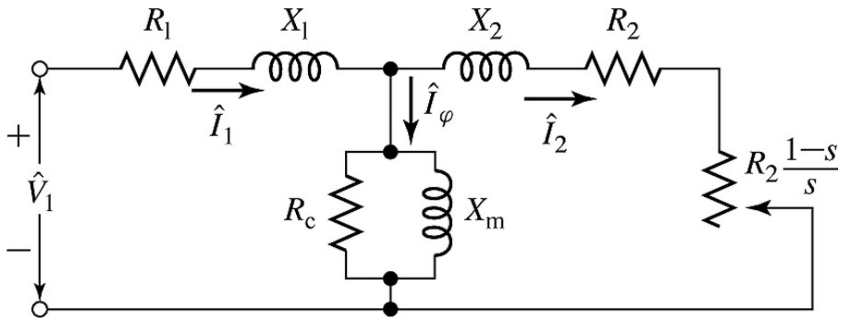
Reference: Ned Mohan, *Power Electronics*, 3d edition

Example: Induction Motor Calculations

- *Fitzgerald*, Example 6.1
- A 3-phase, 2 pole, 60 Hz machine runs at 3502 RPM. The input power is 15.7 kW. The terminal current is 22.6A. The stator winding resistance is 0.2 Ohms per phase. Find the power dissipated in the rotor



Example: Induction Motor Calculations



The stator power is:

$$P_{stator} = 2I_1^2 R_1 = (3)(22.6^2)(0.2) = 306W$$

The airgap power is:

$$P_{gap} = P_{input} - P_{stator} = 15.7kW - 0.3kW = 15.4kW$$

The synchronous speed of this machine is 3600 rpm for a 2-pole machine. The slip is:

$$s = \frac{3600 - 3502}{3600} = 0.0272$$

From the slip and the gap power we find the rotor loss:

$$P_{rotor} = sP_{gap} = (0.0272)(15.4kW) = 419W$$

Example: LIM Calculations

- *Fitzgerald*, Problem 6.4

Linear induction motors have been proposed for a variety of applications including high-speed ground transportation. A linear motor based on the induction-motor principle consists of a car riding on a track. The track is a developed squirrel-cage winding, and the car, which is 4.5 m long and 1.25 m wide, has a developed three-phase, 12-pole-pair armature winding. Power at 75 Hz is fed to the car from arms extending through slots to rails below ground level.

a. What is the synchronous speed in km/hr?

b. Will the car reach this speed? Explain your answer.

c. What is the slip if the car is traveling 95 km/hr? What is the frequency of the track currents under this condition?

d. If the control system controls the magnitude and frequency of the car currents to maintain constant slip, what is the frequency of the armature-winding currents when the car is traveling 75 km/hr? What is the frequency of the track currents under this condition?

Example: LIM Calculations

(a) The wavelength of the winding is:

$$\beta = \frac{4.5m \;\; for\, 12 \;\; pole \;\; pairs}{12} = 0.375m$$

The synchronous speed is:

$$v = \beta f_e = (0.375)(75) = 28 \; m/s = 101 \; km/hr$$

(b) This will never reach synchronous speed because it's an induction motor

Example: LIM Calculations

(c) Slip is found by:

$$s = \frac{101 - 95}{101} = 0.062$$

Induced track currents are at frequency:

$$f_t = sf_e = (0.062)(75) = 4.66\ Hz$$

(d) Synchronous velocity is:

$$v_s = \frac{75}{1 - s} = 80\ km / hr$$

Electrical frequency is found by scaling the original 75 Hz electrical frequency by 80/101:

$$f_e = 75 \times \frac{80}{101} = 59 Hz$$

The track current frequency is simply found:

$$f_t = sf_e = (0.062)(59) = 3.6 Hz$$

National Electrical Code Motor Ratings

Table 430.150 Full-Load Current, Three-Phase Alternating-Current Motors

The following values of full-load currents are typical for motors running at speeds usual for belted motors and motors with normal torque characteristics.

Motors built for low speeds (1200 rpm or less) or high torque may require more running current, and multispeed motors will have full-load current varying with speed. In these cases, the nameplate current rating shall be used.

The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120, 220 to 240, 440 to 480, and 550 to 600 volts.

	Induction-Type Squirrel Cage and Wound Rotor (Amperes)							Synchronous-Type Unity Power Factor* (Amperes)			
Horsepower	115 Volts	200 Volts	208 Volts	230 Volts	460 Volts	575 Volts	2300 Volts	230 Volts	460 Volts	575 Volts	2300 Volts
½	4.4	2.5	2.4	2.2	1.1	0.9	—	—	—	—	—
¾	6.4	3.7	3.5	3.2	1.6	1.3	—	—	—	—	—
1	8.4	4.8	4.6	4.2	2.1	1.7	—	—	—	—	—
1½	12.0	6.9	6.6	6.0	3.0	2.4	—	—	—	—	—
2	13.6	7.8	7.5	6.8	3.4	2.7	—	—	—	—	—
3	—	11.0	10.6	9.6	4.8	3.9	—	—	—	—	—
5	—	17.5	16.7	15.2	7.6	6.1	—	—	—	—	—
7½	—	25.3	24.2	22	11	9	—	—	—	—	—
10	—	32.2	30.8	28	14	11	—	—	—	—	—
15	—	48.3	46.2	42	21	17	—	—	—	—	—
20	—	62.1	59.4	54	27	22	—	—	—	—	—
25	—	78.2	74.8	68	34	27	—	53	26	21	—

HSST Maglev

- Uses short stator LIM

Figure 1: HSST Linimo maglev vehicles for the Tobu Kyuryo Line in Nagoya, Japan

Reference: Federal Transit Authority Report FTA-DC-26-7002.2004.01, “Comparison of Linear Synchronous and Induction Motors”

HSST Maglev

- Uses short stator LIM

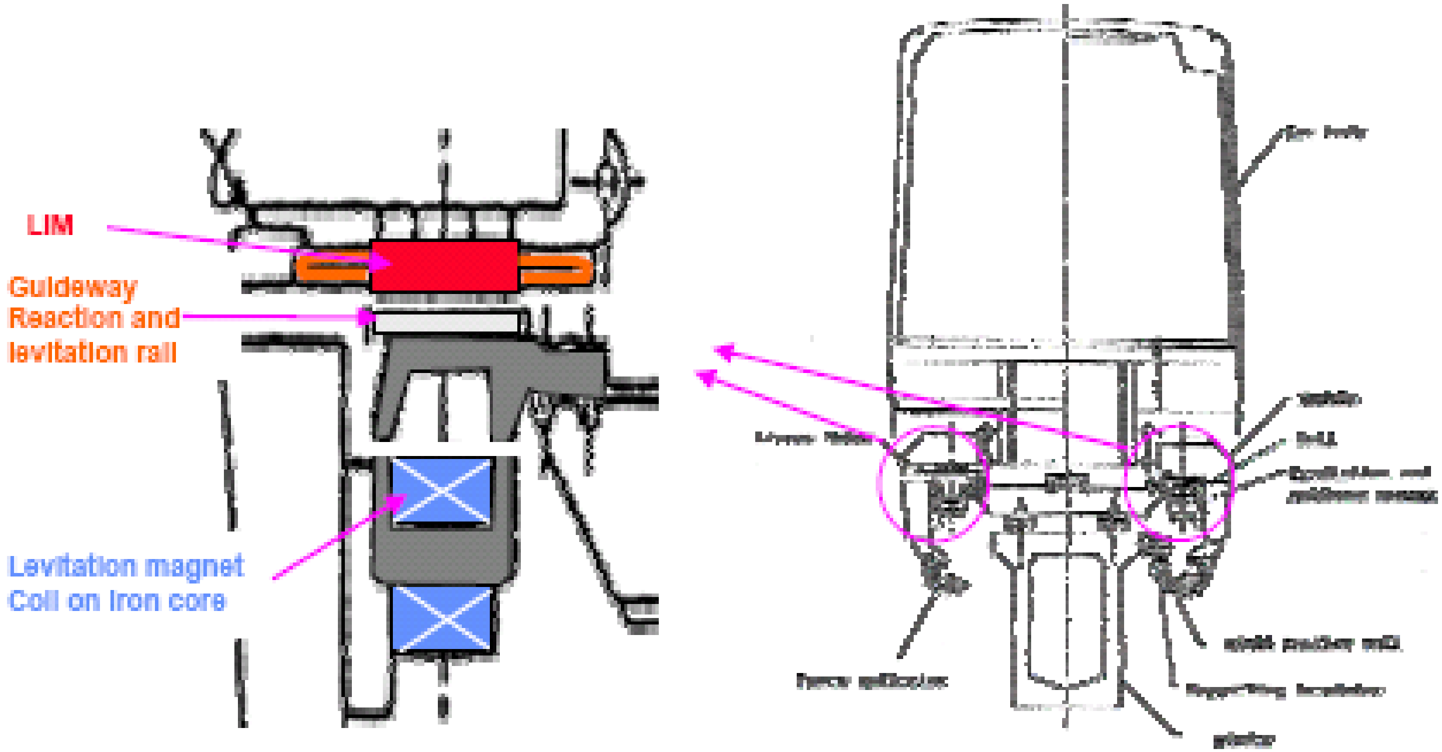


Figure 2: Close-up of propulsion/levitation module for LIM.

Reference: Federal Transit Authority Report FTA-DC-26-7002.2004.01, “Comparison of Linear Synchronous and Induction Motors”

HSST Maglev

- Uses short stator LIM

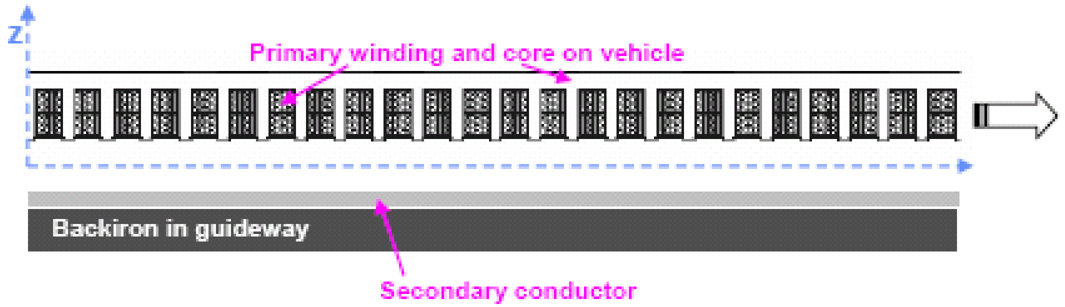


Figure 3: Side-view, cross-section of single-sided LIM components.

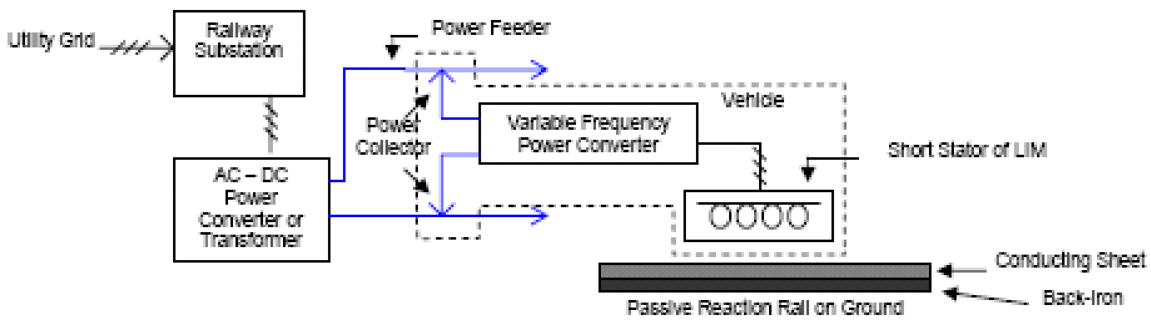
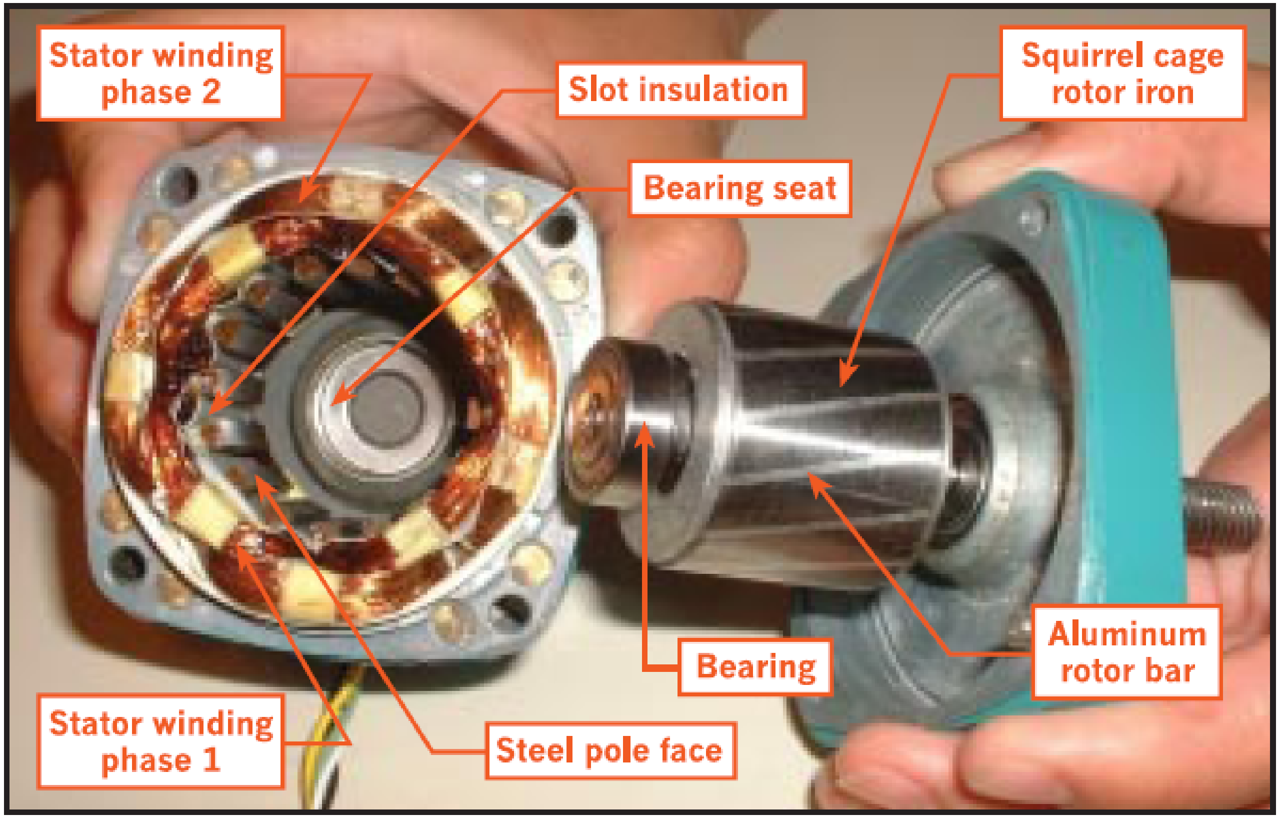


Figure 4: Block diagram of the power circuit for the LIM.

Reference: Federal Transit Authority Report FTA-DC-26-7002.2004.01, “Comparison of Linear Synchronous and Induction Motors”

Basic Squirrel Cage Induction Motor

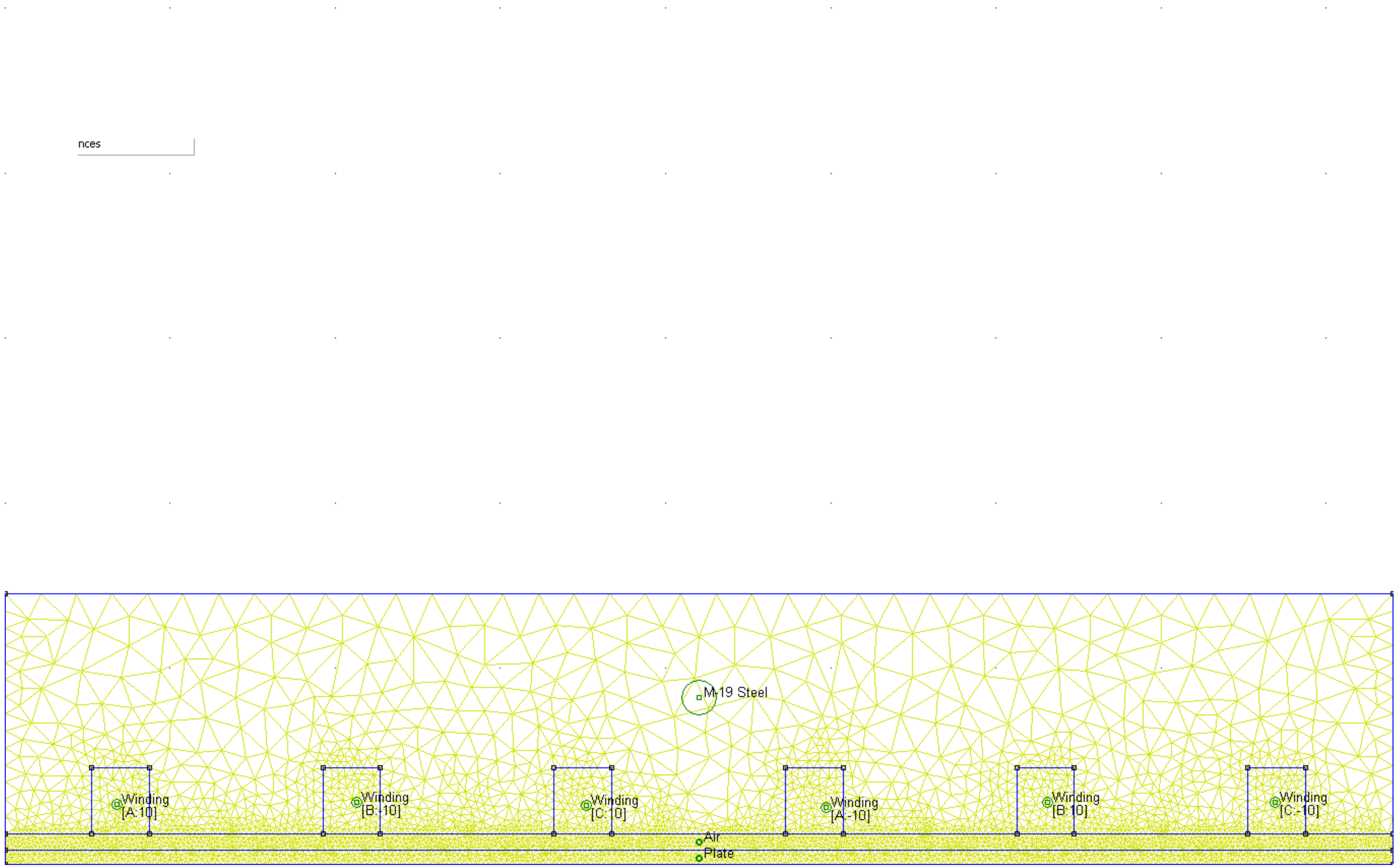


Typical two-phase squirrel cage induction motor.

Reference: Ralph Fehr III, “Basics of AC Machines,” EC&M, September 2003

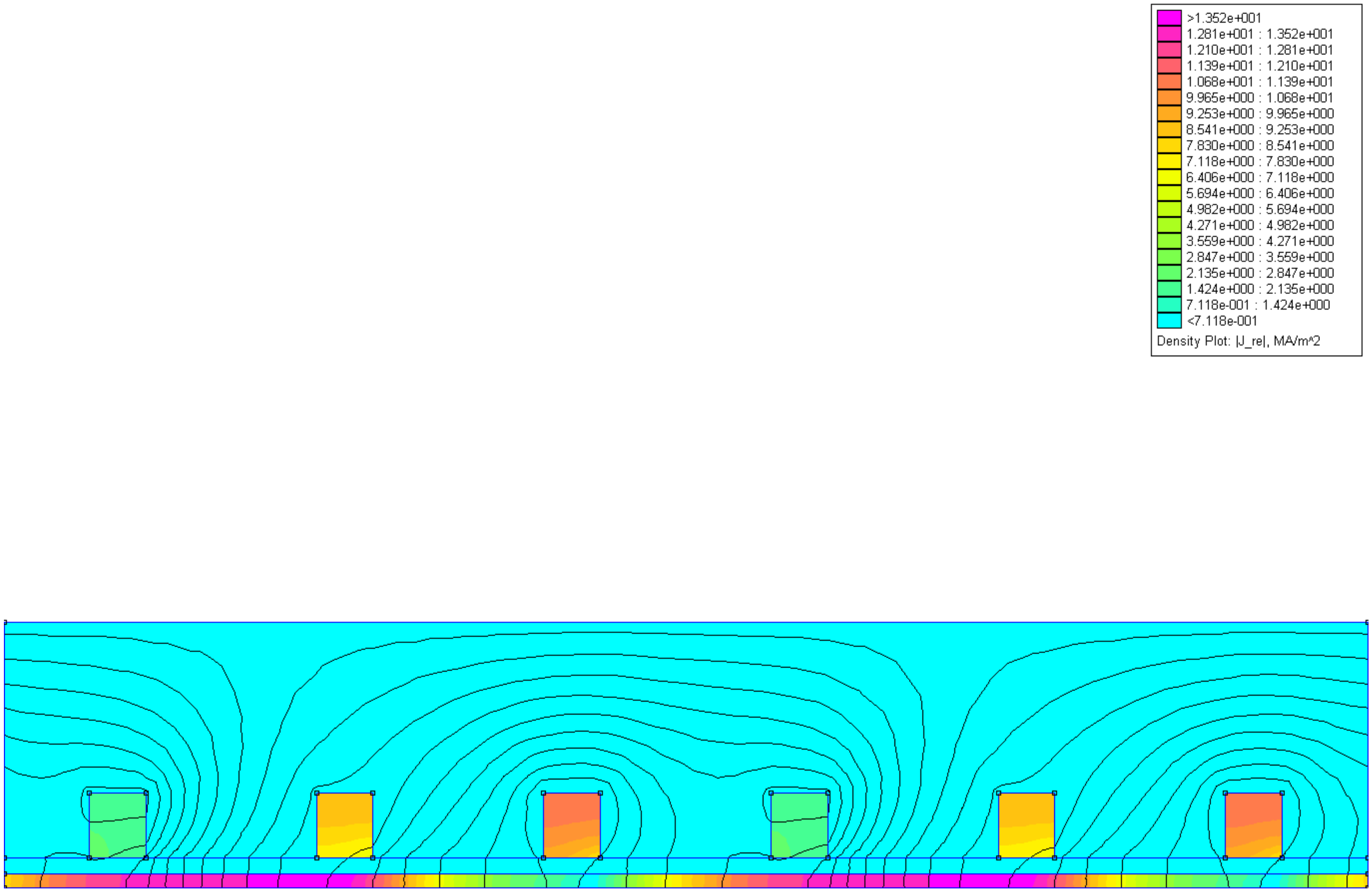
Double-Sided LIM FEA

- By symmetry, we need only simulate ½ of the motor



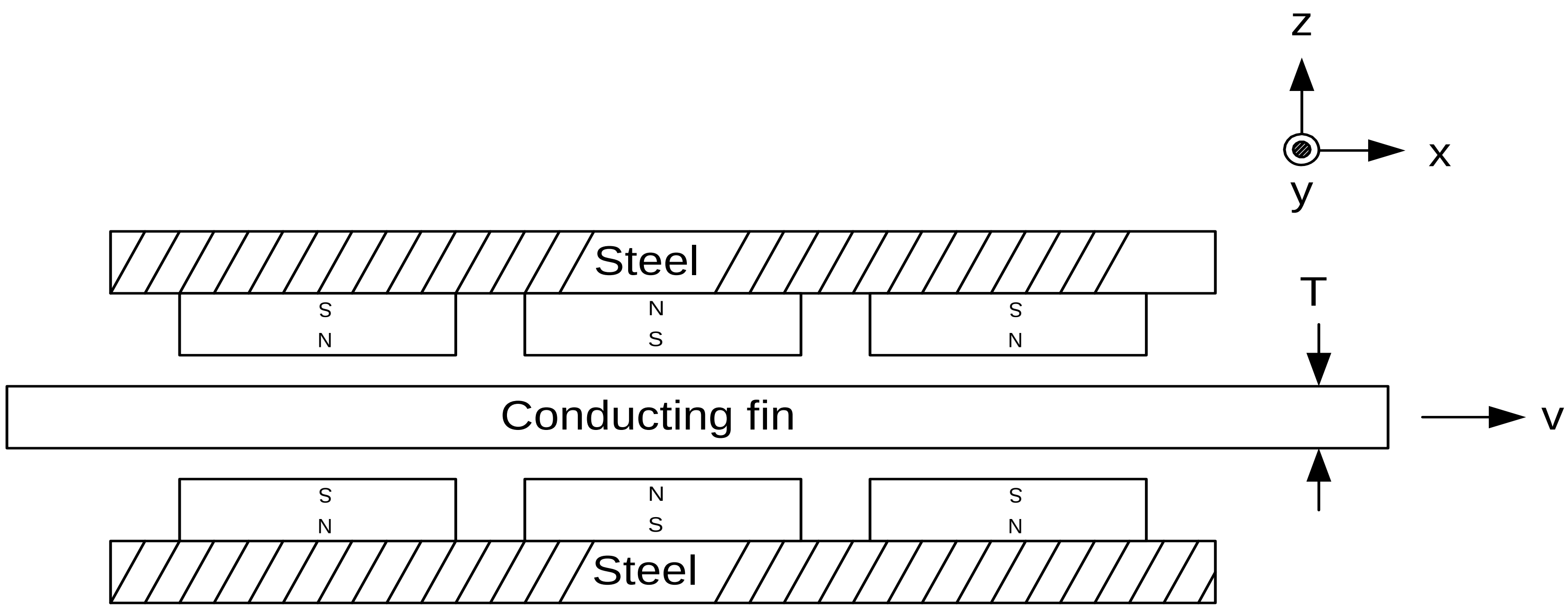
Double-Sided LIM FEA

- By symmetry, we need only simulate ½ of the motor



Basic Eddy Current Brake

- Magnetic field created by high strength magnets
- Relative motion between field and conducting fin creates eddy currents and hence braking force
- Design variables: magnetic strength, fin material and fin thickness, airgap



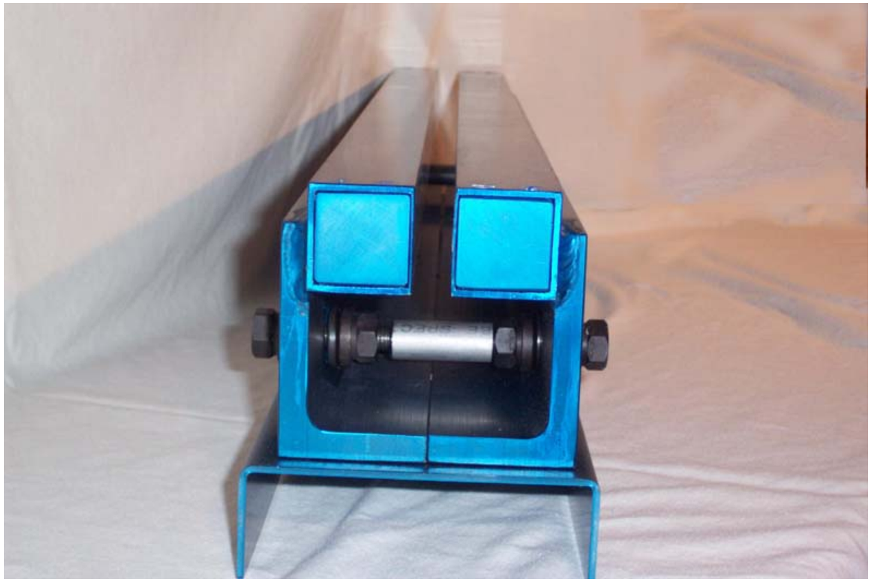
Magnetic Induction in ECBs

- Relative motion between permanent magnets and conducting sheet means that there is a time-varying magnetic field impinging on the sheet
  - Magnets <u>or</u> conducting sheet can be moving; it's relative movement that's important
- This time varying magnetic field creates circulating (eddy) currents in conducting sheet
  - Magnetic induction is the principle by which these eddy currents are induced (by Faraday's Law)
- Eddy currents mean power dissipation in sheet, and a magnetic drag force acting on the sheet

$$\frac{d\vec{B}}{dt} \rightarrow \vec{E} \rightarrow \vec{J} \rightarrow \langle P_{diss} \rangle \rightarrow forces$$

Eddy Current Brake

- Implemented on roller coasters in the US
  - (Magnetar, Inc., Seal Beach CA)
- No contacting parts



Reference: http://www.magnetarcorp.com

Induction Brake

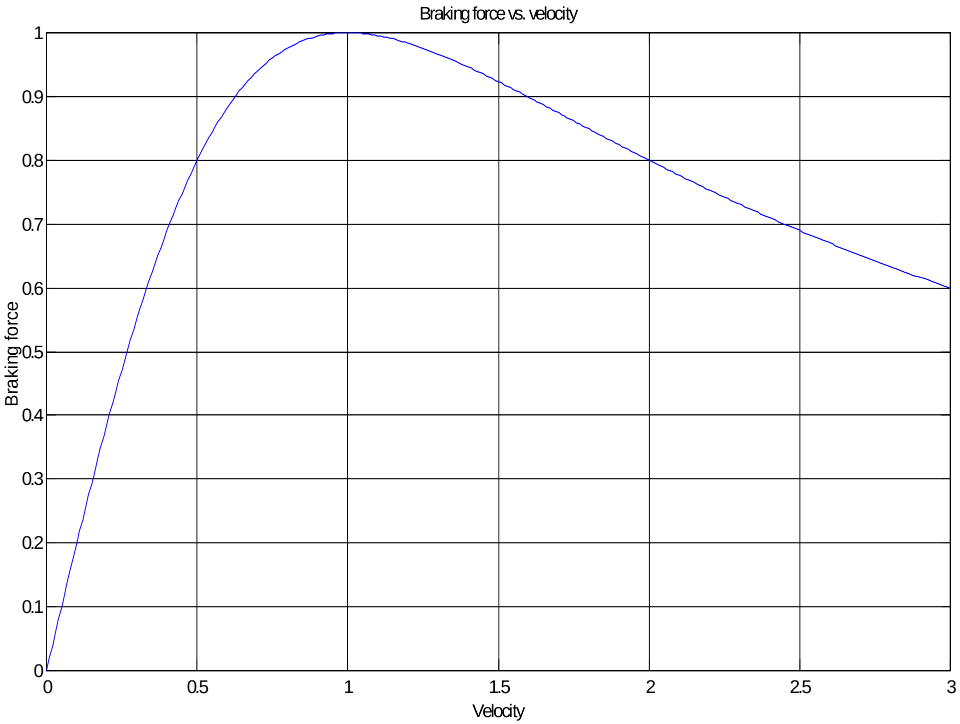
Reference: www.magnetarcorp.com

Braking Force vs. Velocity

- From electrodynamic analysis, braking force is:

$$f_b = F_o \frac{v v_{pk}}{v^2 + v_{pk}^2}$$

- F_o depends on magnet strength, airgap, and magnet area

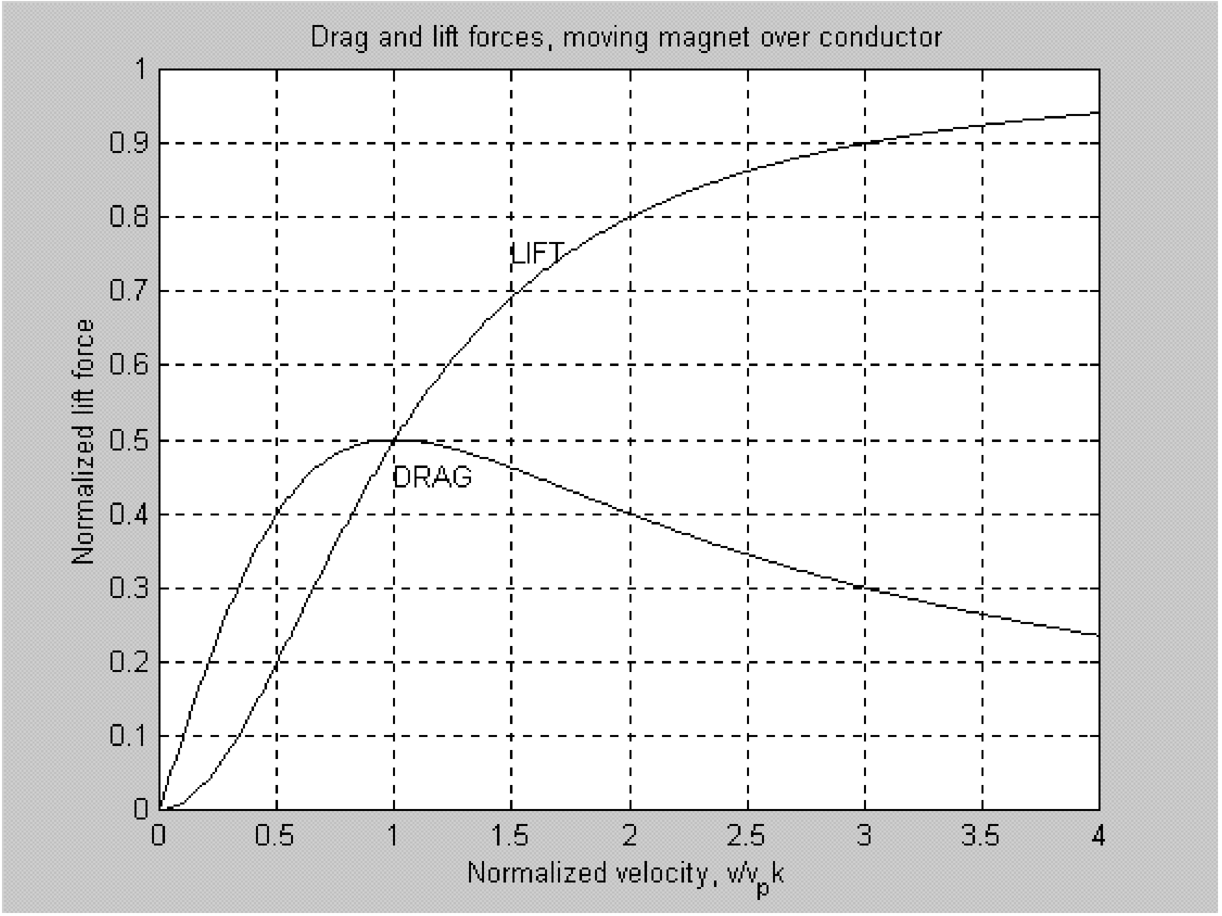


Comment on Braking Force Profile

- This electrodynamic result is also found in electrodynamic Maglev, (e.g. Japanese superconducting EDS, General Atomics' permanent magnet EDS, MIT experiments of early '70s and mid '90s).
- In Maglev you go to great effort to <u>reduce</u> drag
- In eddy current brakes, you try to <u>maximize</u> drag

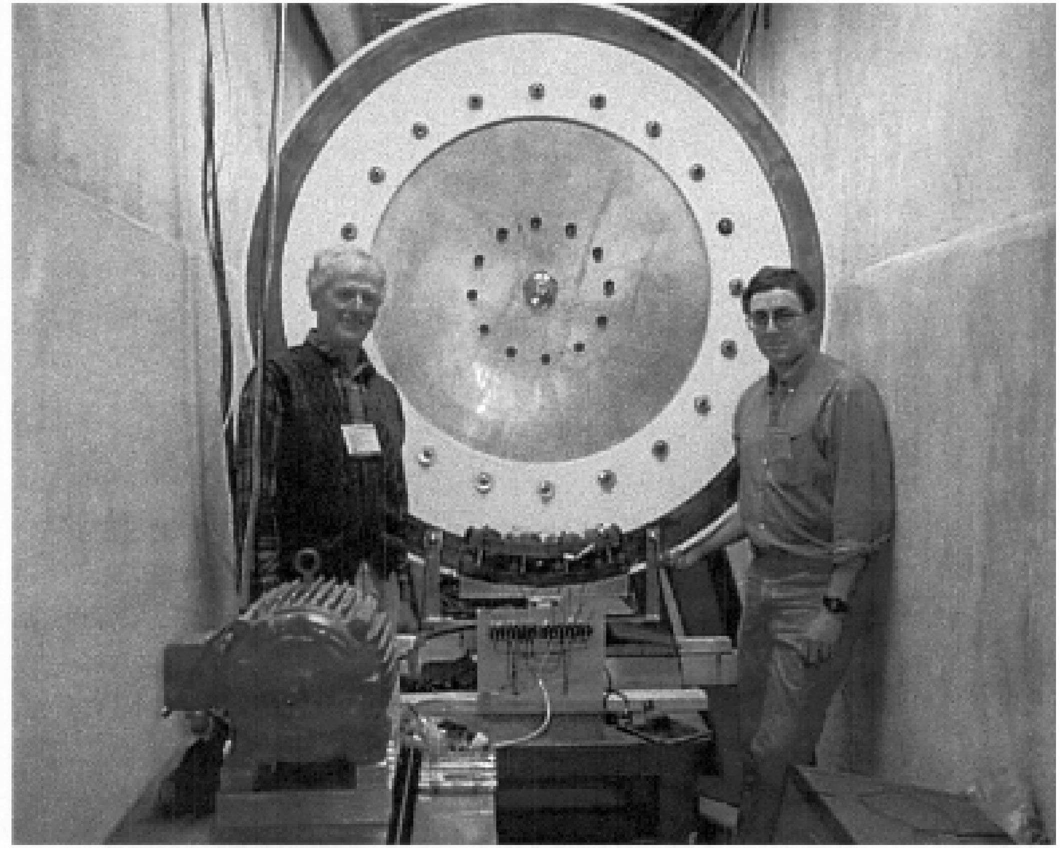
EDS Maglev Lift and Drag Forces

- For example, moving permanent or electromagnet over a conducting plate



MIT EDS Maglev Test Facility

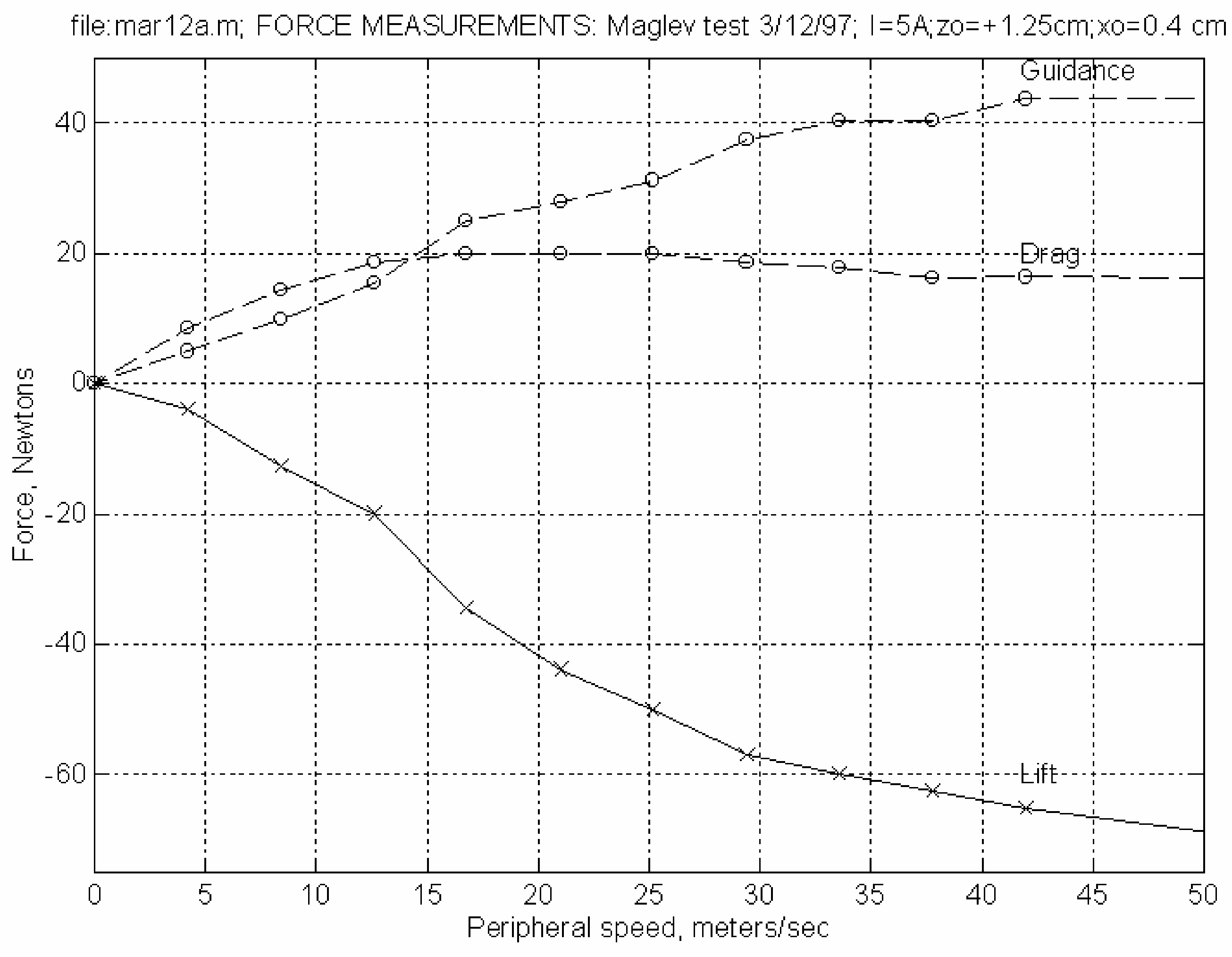
- 2 meter diameter test wheel
- Max. speed 1000 RPM (84 m/s)
- For testing “flux canceling” HTSC Maglev
- Sidewall levitation



References:

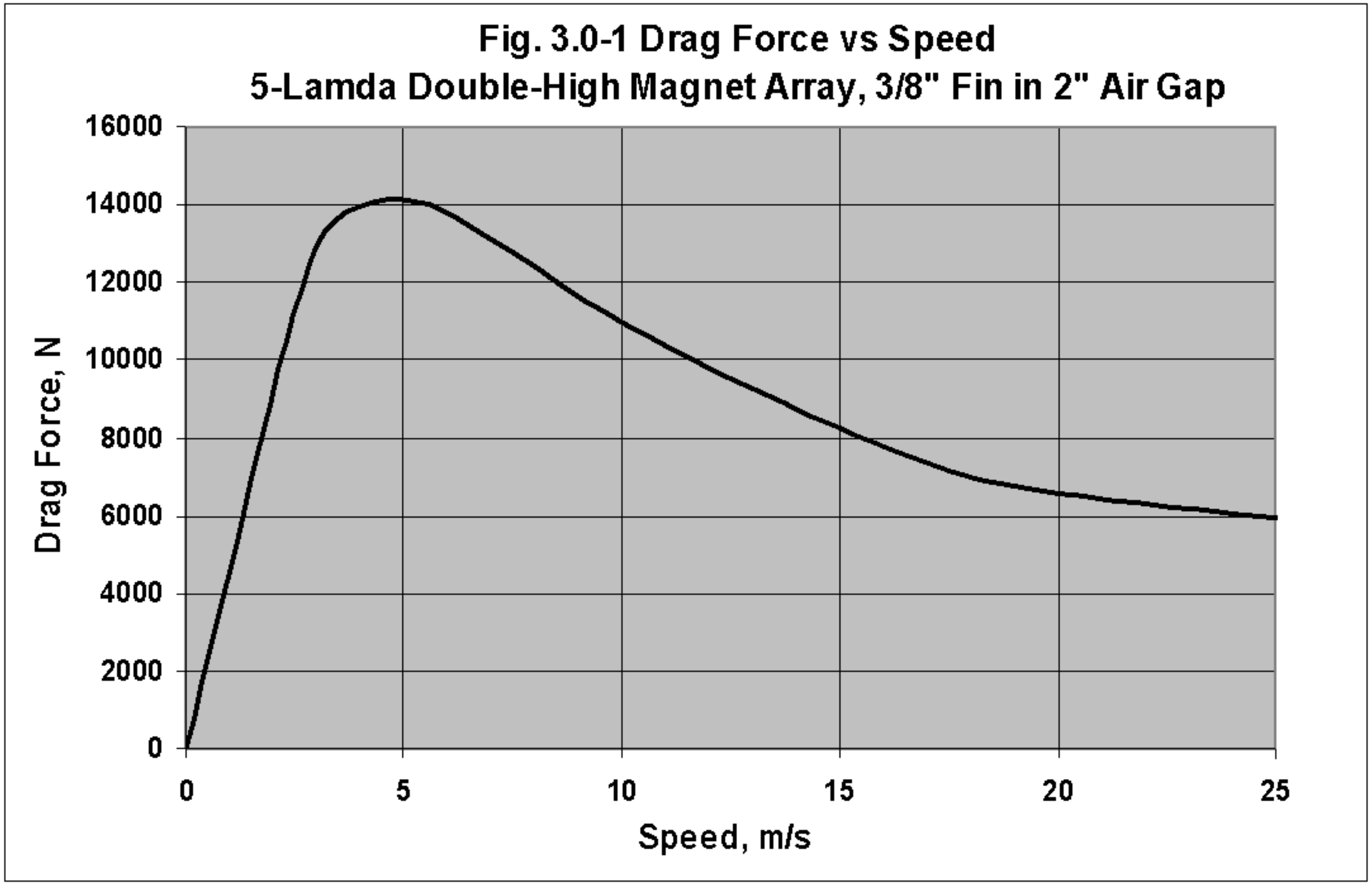
1. Marc T. Thompson, Richard D. Thornton and Anthony Kondoleon, “Scale Model Flux-Canceling EDS Maglev Suspension --- Part I: Design and Modeling,” *IEEE Transactions on Magnetics*, vol. 35, no. 3, May 1999, pp. 1956-1963
2. Marc T. Thompson and Richard D. Thornton, “Scale Model Flux-Canceling EDS Maglev Suspension --- Part II: Test Results and Scaling Laws,” *IEEE Transactions on Magnetics*, vol. 35, no. 3, May 1999, pp. 1964-1975

MIT EDS Test Results



Back to ECBs: Result of 3D FEA

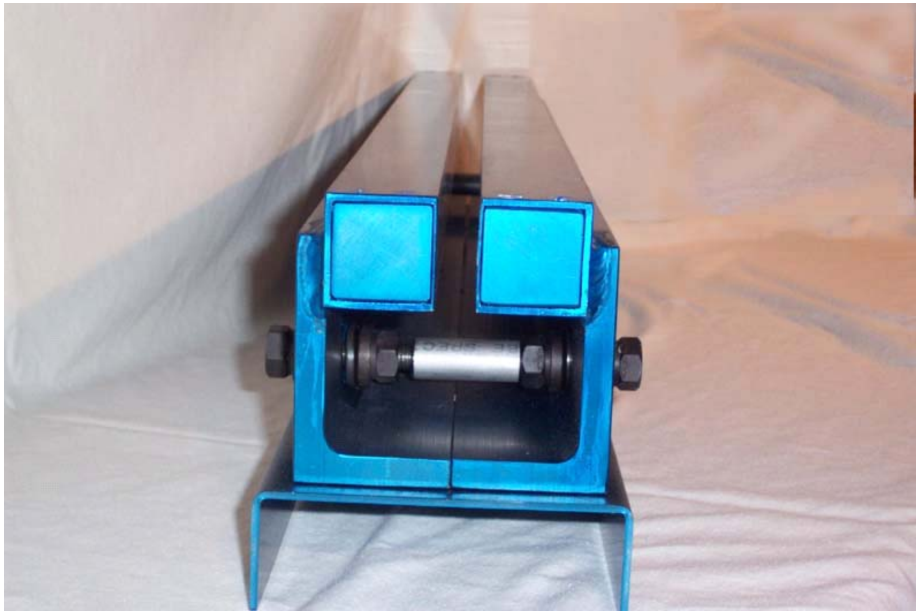
- Note that braking force is maximum at the "drag peak" velocity



3D FEA done by Myatt Consulting, Inc., Norfolk, MA

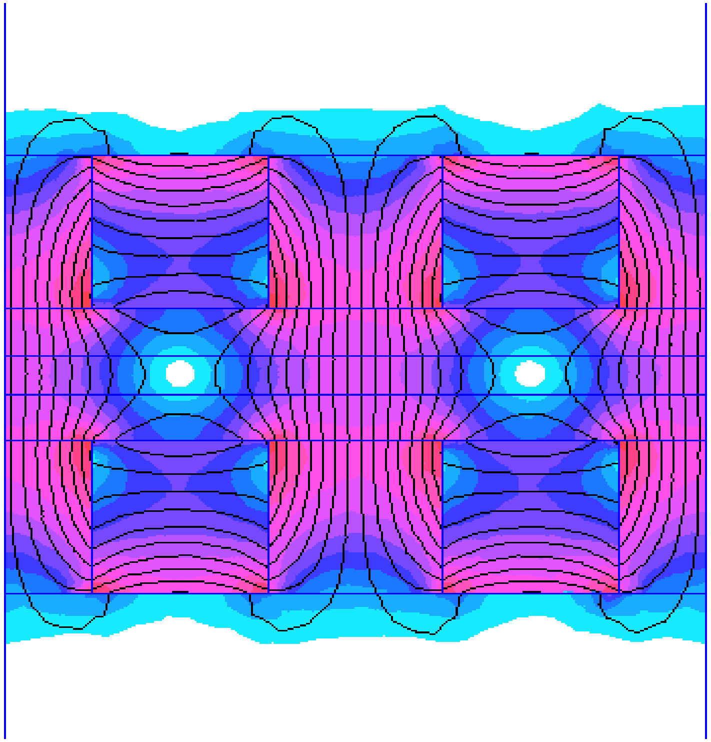
Mechanical Design Issues

- At low speed, force between magnetic rails is attractive
  - North pole is attracted to South pole across the airgap
- At high speed, force between magnetic rails is repulsive
  - Due to induced magnetic poles in the conducting fin
- Therefore, there is a cycling of the net force acting on the magnet mounts as the coaster fin passes through the magnetic airgap



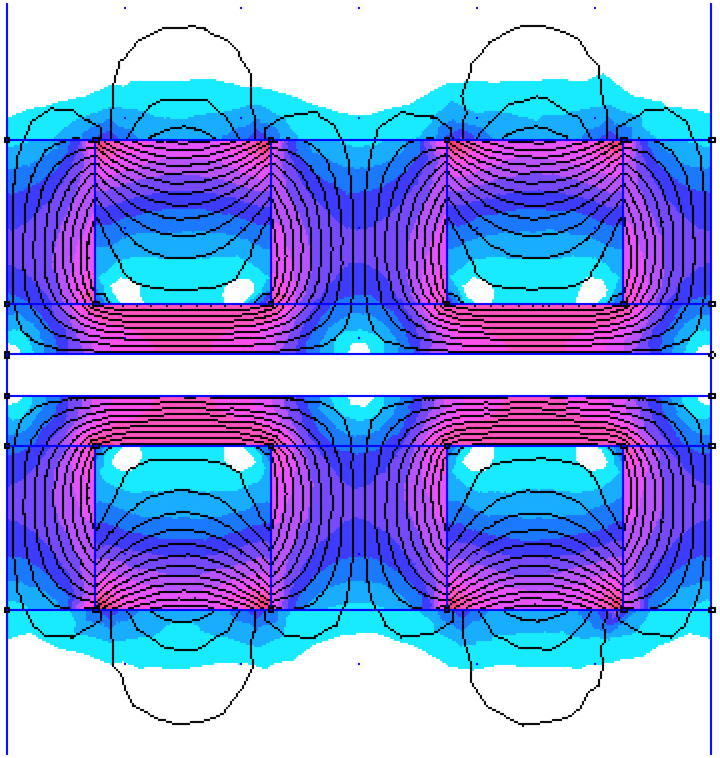
2D FEA: Low Speed Flux Line Plot

- At low speed, force between magnetic rails is attractive
  - North pole attracts to South Pole across airgap



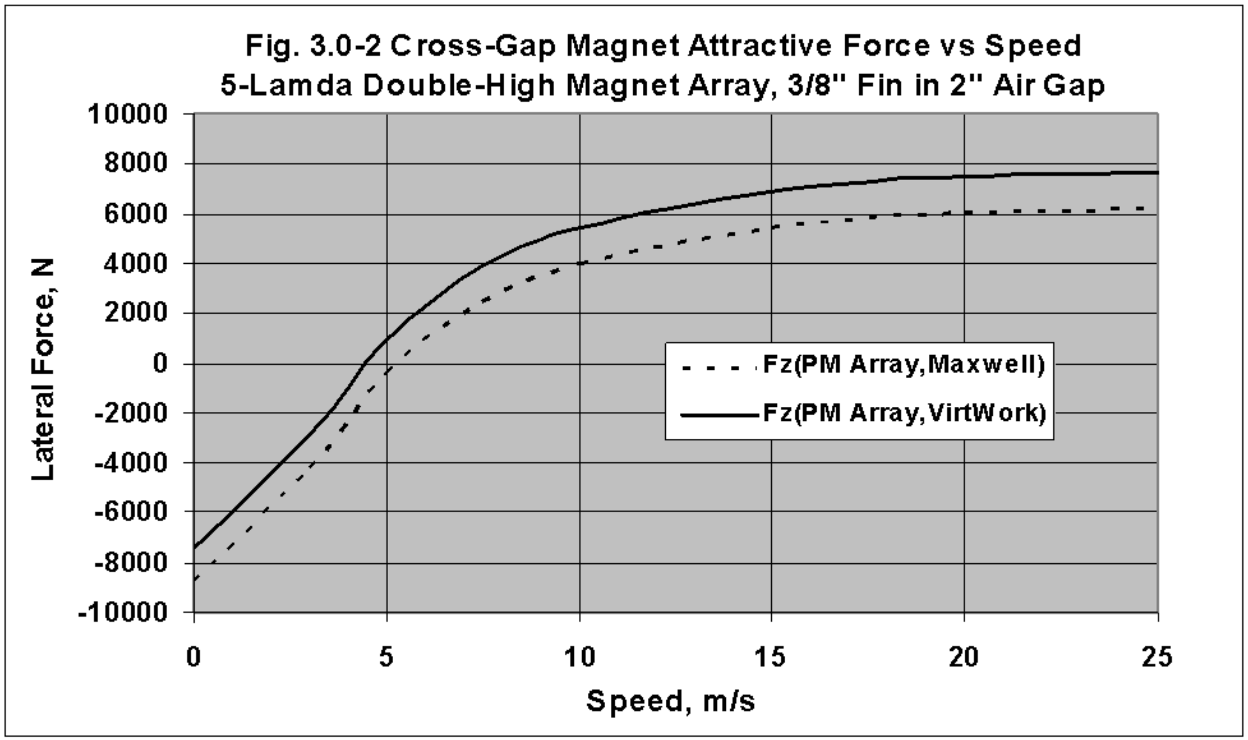
2D FEA: Approximate High Speed Flux Line Plot

- At high speed, force between magnetic rails is repulsive
  - North pole is repelled from induced North pole in conducting fin



Result of 3D FEA for Forces on Magnet Arrays

- Note that force crosses through zero near the “drag peak” velocity



3D FEA done by Myatt Consulting, Inc., Norfolk, MA

Mechanical Design Issues

- Brake magnet mounting rails must withstand this positive-to-negative force cycling when coaster passes through
  - For large brake, this cyclical force can be thousands of pounds, peak-to-peak
- Conducting fin has large shear force during braking, and also a thermal stress
- Approximate number of cycles in lifetime of brake:
  - 20 cars/hour x 12 hours/day x 365 days/year x 10 years = 875,000 cycles
  - Maximum stress in structure of magnet mounts and conducting fins are designed to withstand this fatigue limit with a large safety margin

Thermal Design Issues

- Power is dissipated in conducting fin
  - Heat rise of fin material must be calculated
- Also, be aware of temperature effects on NdFeB magnet material
  - Higher strength material is more sensitive to demagnetization vs. temperature

Table 5.1 Reversible Temperature Coefficients of B_r and H_c

Material	T_c of B_r	T_c of H_c
NdFeB	-0.12	-0.6
SmCo	-0.04	-0.3
Alnico	-0.02	0.01
Ceramic	-0.2	0.3

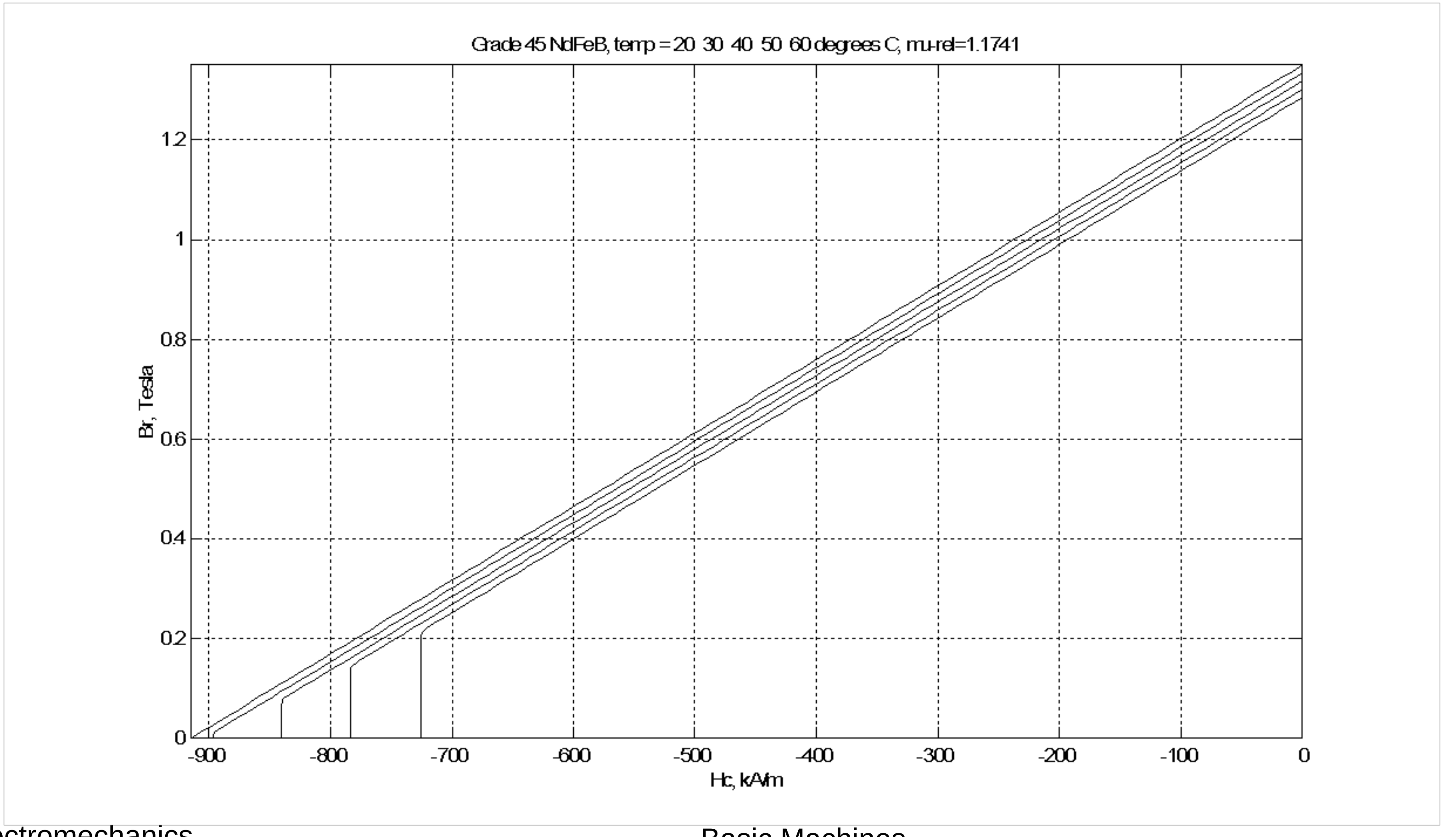
Reference: http://www.magnetsales.com

Heat Rise of Fin

- Braking power is dissipated in conducting fin
- This power is significant ($0.5Mv^2/t_{stop}$ > 500 kW for large coaster moving fast)
- Heat rise of fin depends on heat capacity of fin and on convective heat transfer
- Using thermal circuit analogies, we can use SPICE to simulate temperature rise
  - (More on this later)

Temperature Effects on NdFeB

- High temperature can cause demagnetization of NdFeB
- Higher strength material is more susceptible to temperature-induced demagnetization



Magnetic Flux – Safety Concerns

- Working safety limit: < 5 Gauss DC in passenger cabin for pacemaker wearers, 400 Gauss DC for general public
  - American Conference of Governmental Industrial Hygienists (ACGIH)
  - International Radiation Protection Association (IRPA)
  - International Commission on Non-Ionizing Radiation Protection (ICNIRP)
- ACGIH guideline: < 1 Gauss for 60 Hz

References:

1. ACGIH, *2001 TLVs and BEIs Threshold Limit Values for Chemical Substances and Physical Agents and Bioligical Exposure Indices*, ACGIH, Cincinnati OH, 2001
2. ICNIRP Guidelines, *Health Physics*, Jan. 1994, vol. 66, no. 1

Magnetic Flux – Other Concerns

- 5 Gauss: pacemaker wearers
- 10 Gauss: analog watches, credit cards, magnetic tapes, computer disks can be damaged
- “Few tens of Gauss”: ferromagnetic implants
- 30 Gauss: hazards from flying metallic objects
- 400 Gauss: general public

Reference: ICNIRP Guidelines, *Health Physics*, Jan. 1994, vol. 66, no. 1

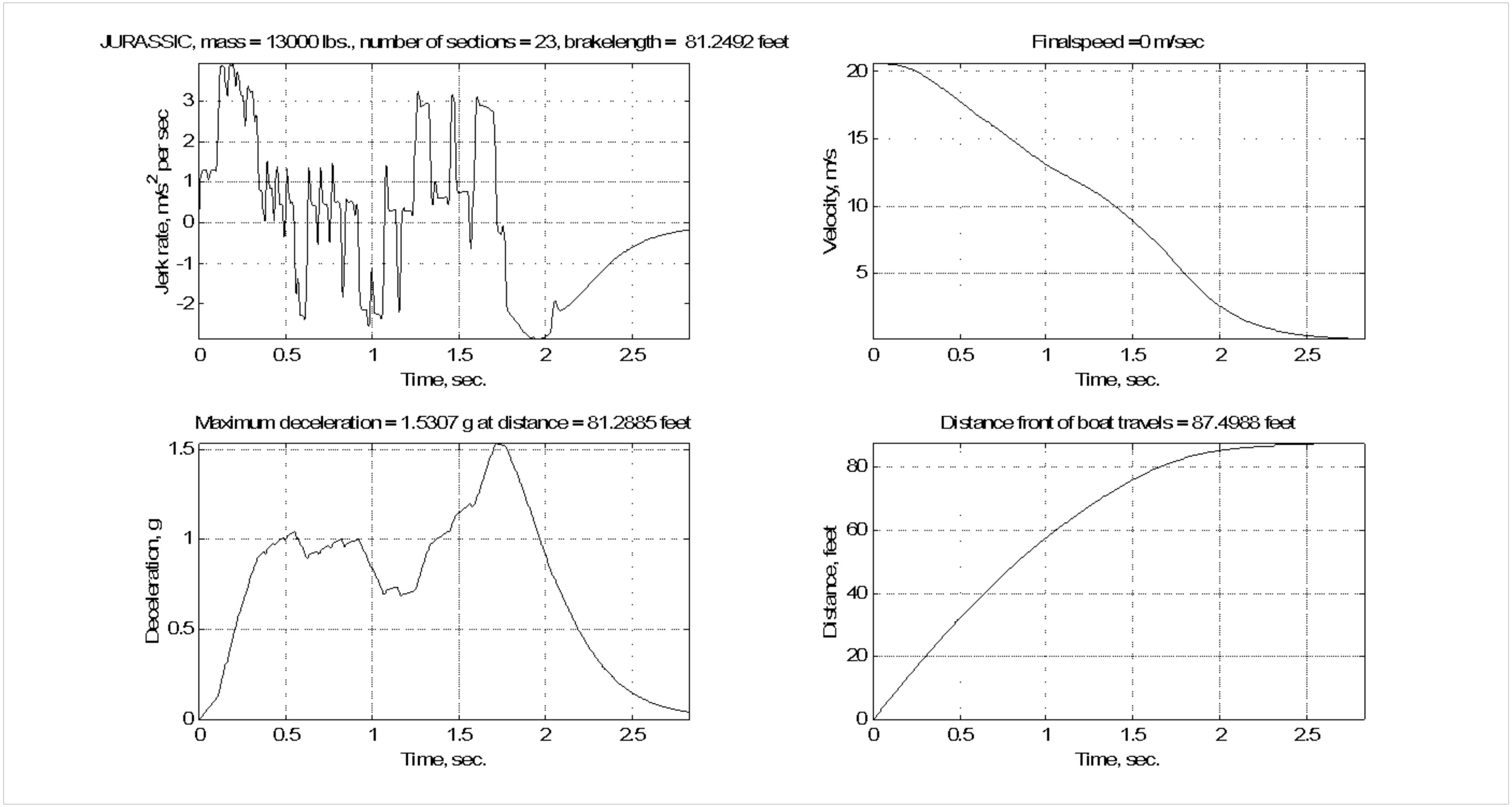
Design Case Study --- Universal Studios

- Issue: Universal Studios' "Jurassic Park" splashdown ride had high G forces and lots of waves in splashdown tank (i.e. water provided all the braking force)
- Specifications
  - Boat weight: 13,000 lbs (9000 lbs. empty weight, 4000 lbs. of passengers)
  - Entry speed into brake: 48 mph from 84 foot drop
- Goal: stop the boat in less than 95 feet and keep G forces at < 1.6G

Case Study --- Jurassic Park

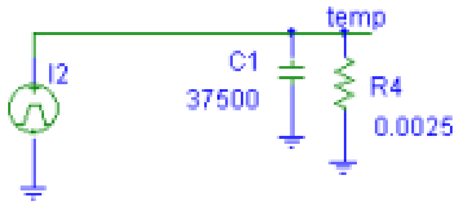
MATLAB-Based ECB Design Simulation

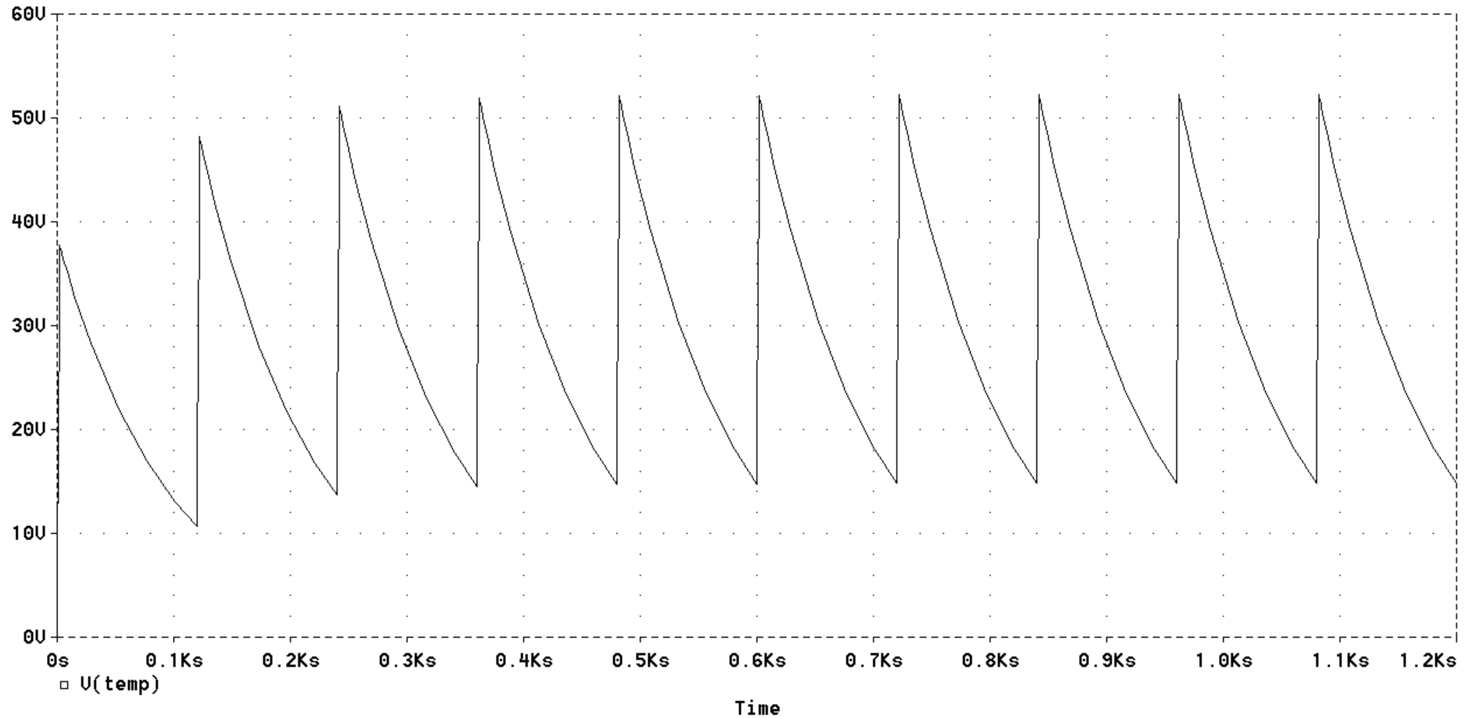
- Shows jerk rate, deceleration, speed and distance traveled



Fin Temp. Rise Thermal Model Using SPICE

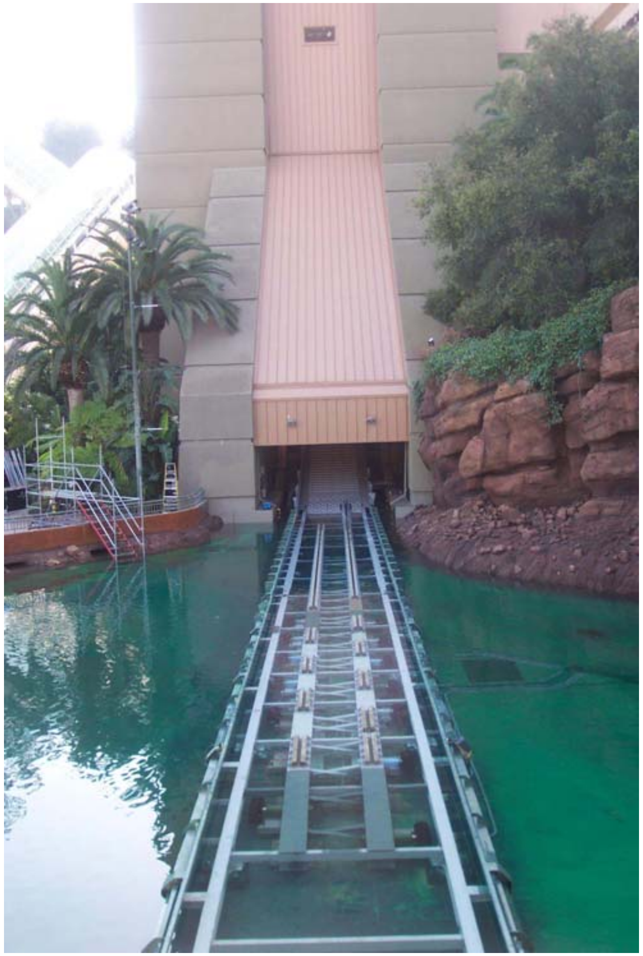
- This model assumes no water (worst case)





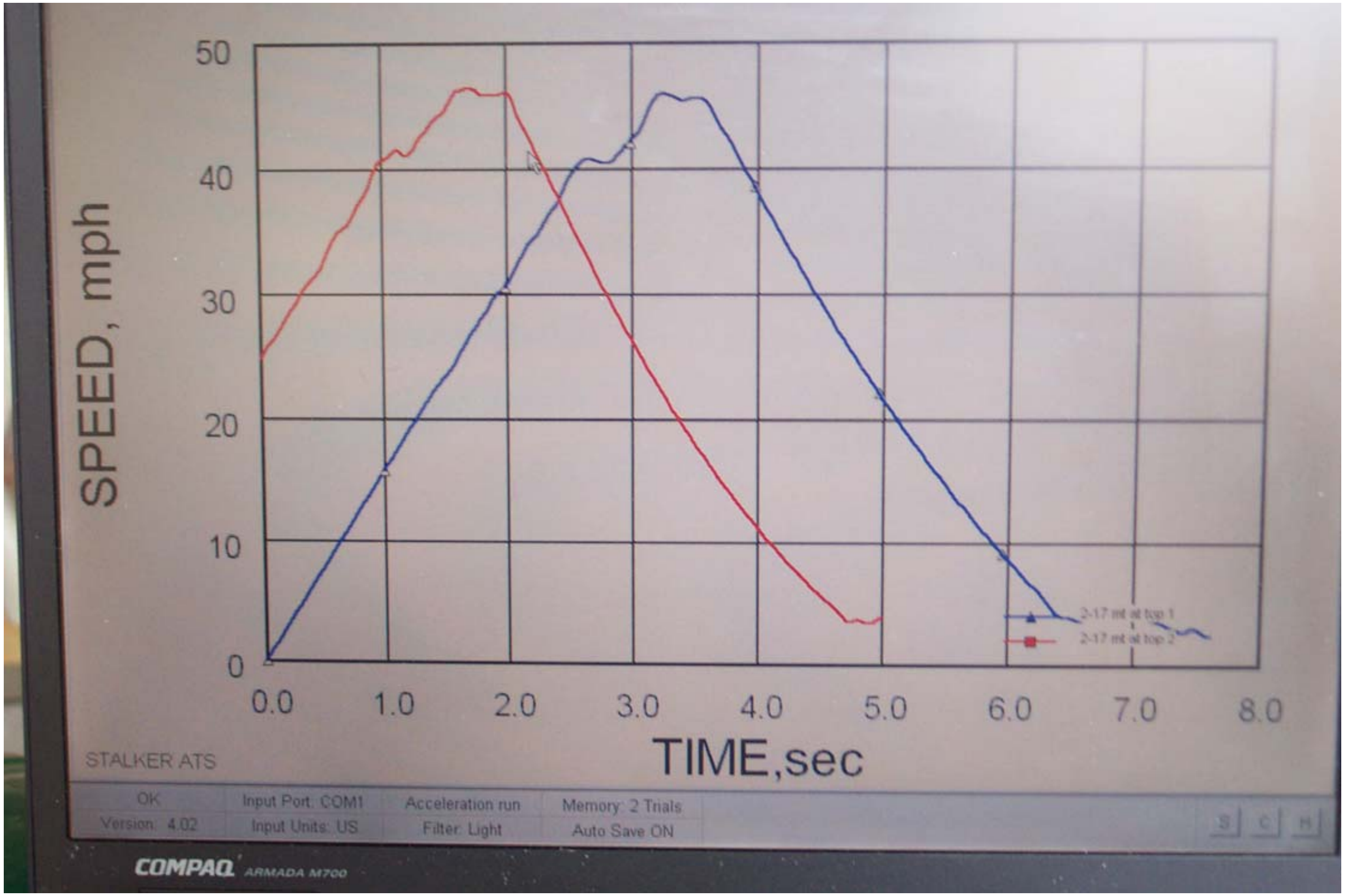
Brake Fabrication

Installation – Hollywood CA



Installation of Test Boat

Test Results --- Radar (2 runs)



Test Results

- Magnetic: Boat is stopped successfully with acceptable G force and jerk rate
  - Stopping performance closely matches simulations for speed, G forces, etc.
- Mechanical: Structural supports and fins sized to withstand 10^6+ cycles
- Thermal: Water keeps fins and magnets < 80F
- Flux: Stray flux less than 5 Gauss in passenger cabin

Summary and Overview of the 3 Days

- The major topics covered have included:
  - Some basic circuit concepts
  - Power
  - Harmonics
  - 3 phase circuits
  - Maxwell’s equations
  - Soft magnetic materials
  - Hard (permanent magnet) materials
  - Electromechanical energy conversion
  - Forces and torques
  - Rotating MMFs
  - Basic machines
  - Synchronous machines
  - Induction machines