

Fundamentals of AC Machines

1

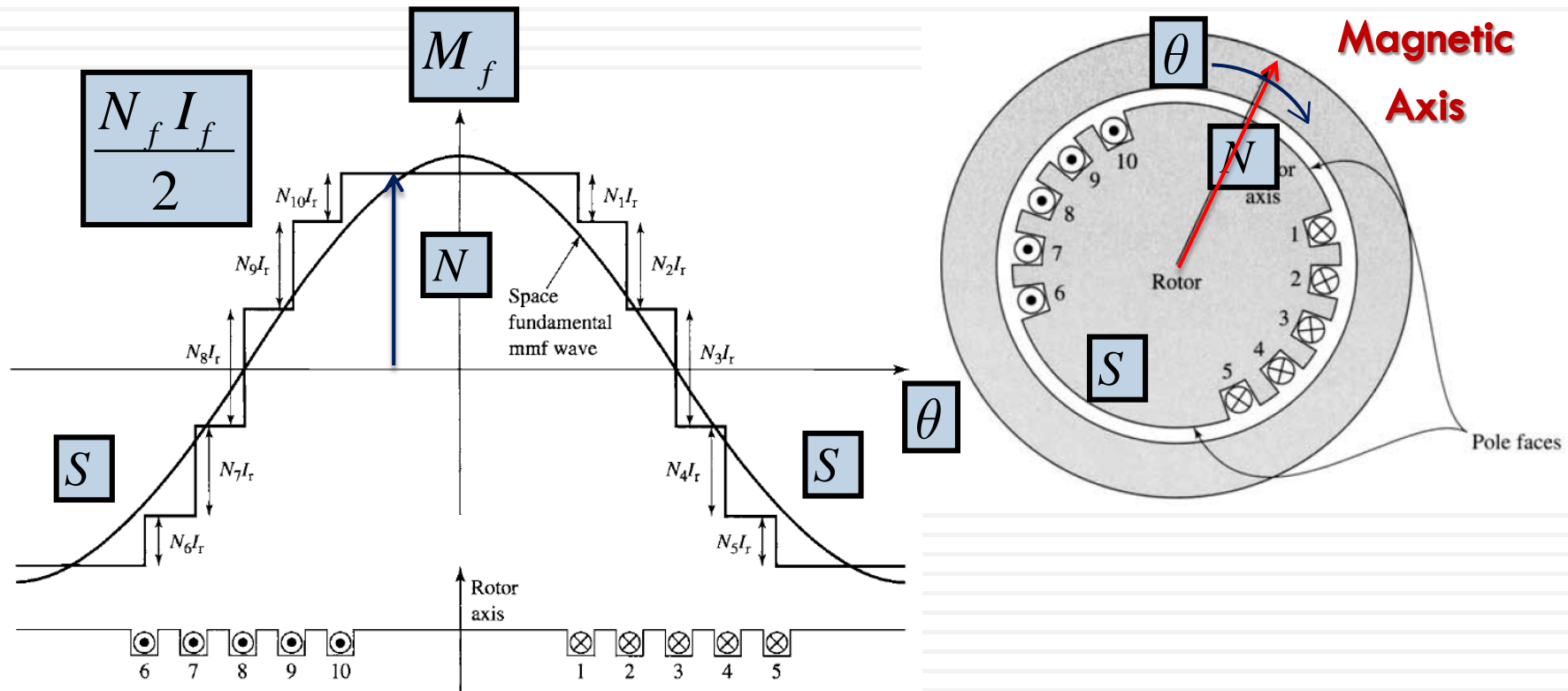
- Magnetic Field Production and Distribution
 - DC Machines
 - Synchronous Machines
 - Induction Machines
- Generated (induced) Voltages
 - Synchronous Machines
 - Induction Machines

Generated Voltage (EMF)

2

Synchronous Machines

Non-salient poles

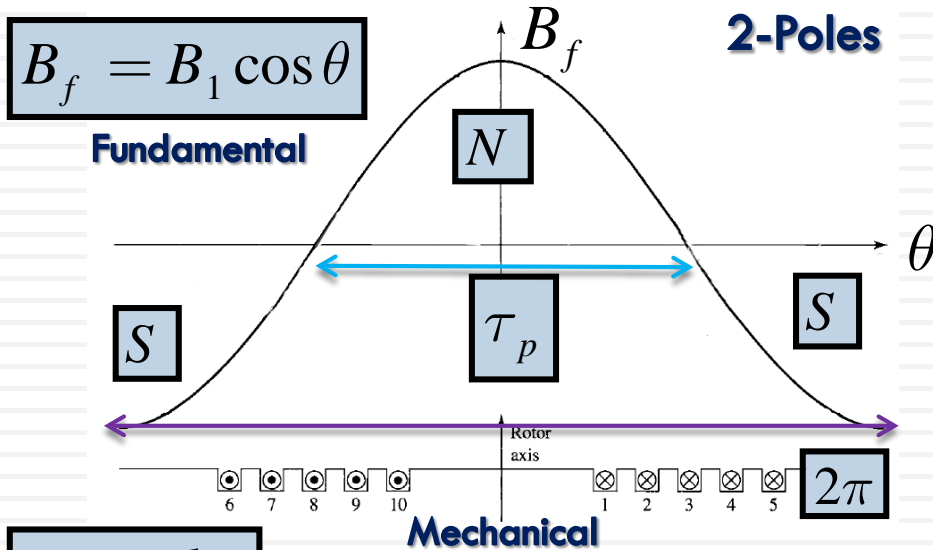


Generated Voltage (EMF)

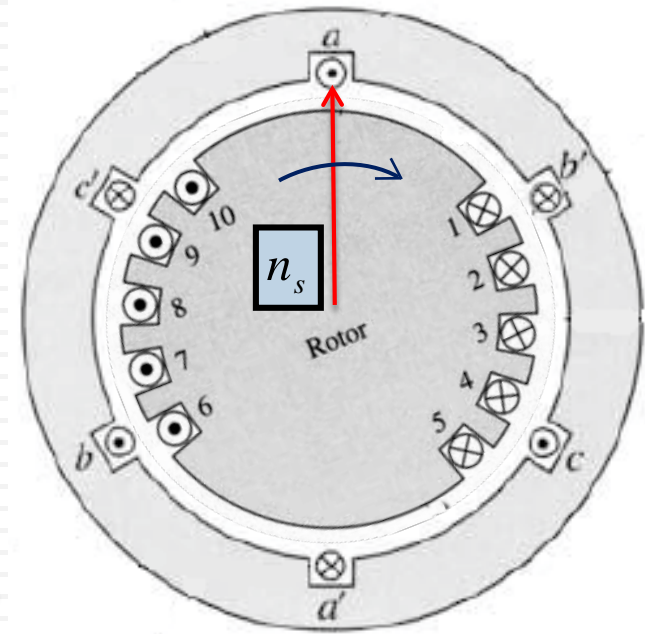
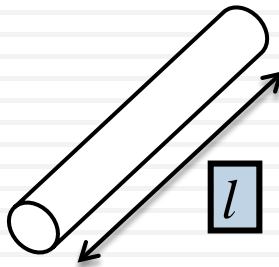
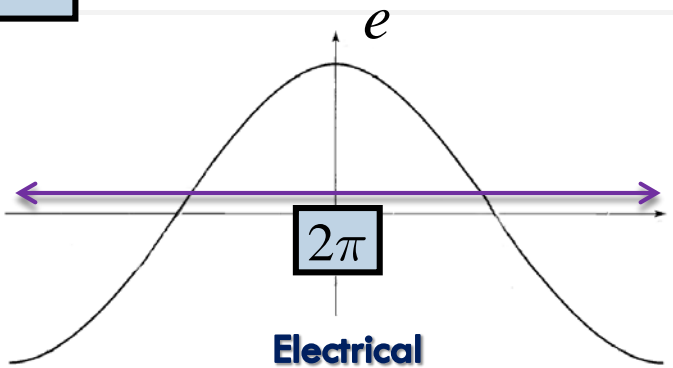
3

Synchronous Machines

Electrical Angle vs. Mechanical Angle



$e = Blv$



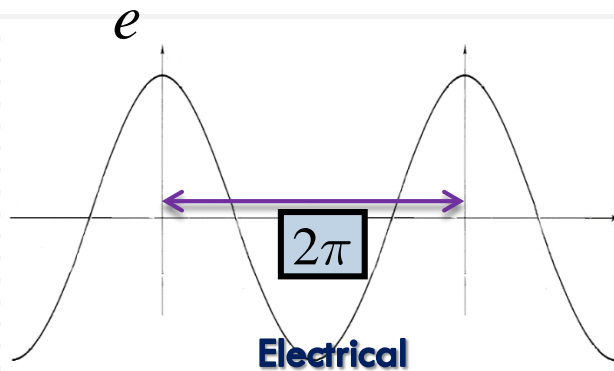
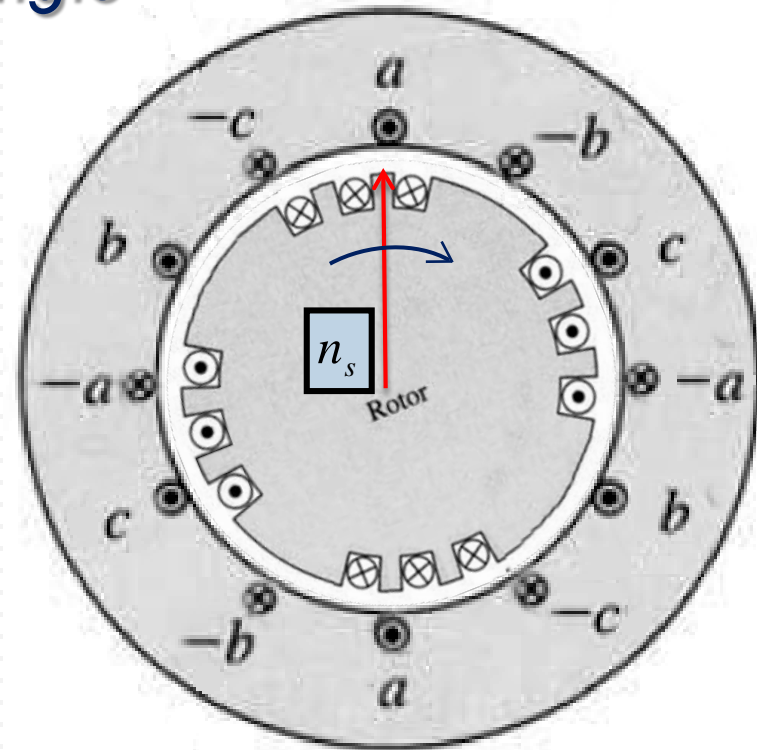
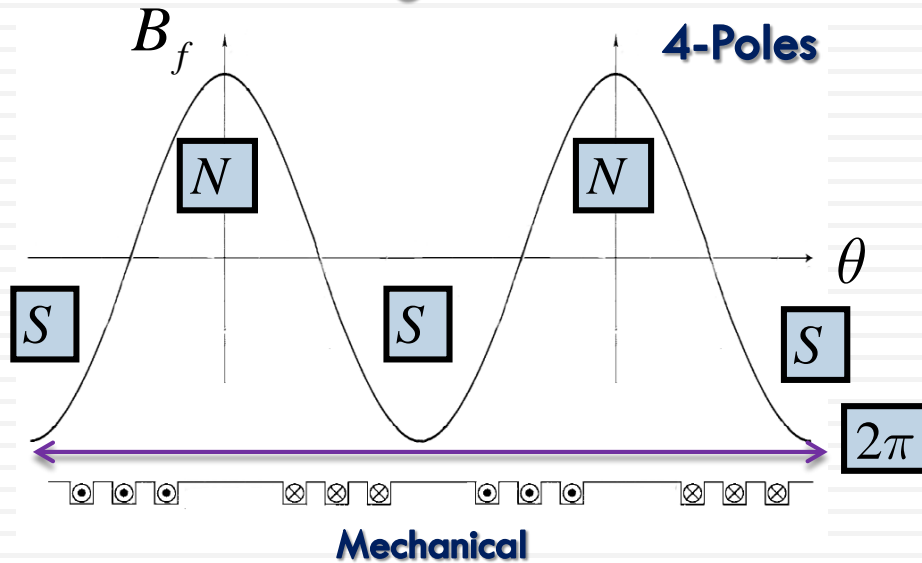
τ_p Pole Pitch

Generated Voltage (EMF)

4

Synchronous Machines

Electrical Angle vs. Mechanical Angle



Generated Voltage (EMF)

5

Synchronous Machines

Frequency of the generated EMF

	Mech. Angle	Elect. Angle
No. of poles	No. of mech. Revolutions ($\theta = \theta_m$)	No. of time cycles ($\omega_e t = \theta_e$)
2	1 ($2\pi(360^\circ)$)	1 (2π)
4	1 ($2\pi(360^\circ)$)	2 ($2*2\pi$)
6	1 ($2\pi(360^\circ)$)	3 ($3*2\pi$)
2p	n_s (rpm)	pn_s (cycles/min)

$$f = \frac{pn_s}{60}$$

$$\theta_e = p\theta_m$$

p = no. of pair poles

Generated Voltage (EMF)

6

Synchronous Machines

For One Conductor

$$e = Blv$$

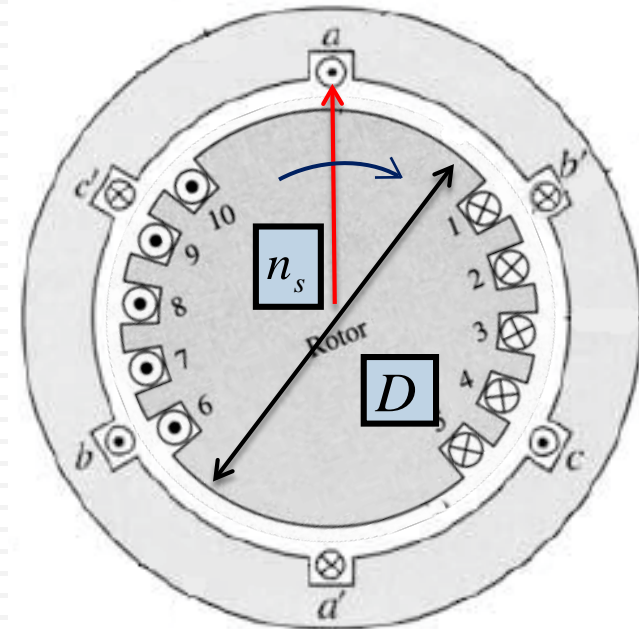
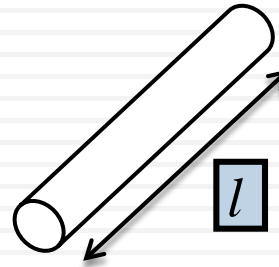
$$B_f = B_1 \cos \theta$$

$$e_1 = B_1 lv \cos \theta$$

$$E_{1m} = B_1 lv$$

$$v = \omega r = \frac{2\pi}{60} n_s \frac{D}{2}$$

$$v = \frac{\pi f D}{p}$$



$$f = \frac{pn_s}{60}$$

Generated Voltage (EMF)

7

Synchronous Machines

$$\phi_{/pole} = \frac{2}{\pi} B_1 \tau_p l$$

$$\tau_p = \frac{\pi D}{2p}$$

$$\phi = \frac{2}{\pi} B_1 \frac{\pi D}{2p} l = \frac{B_1 D l}{p}$$

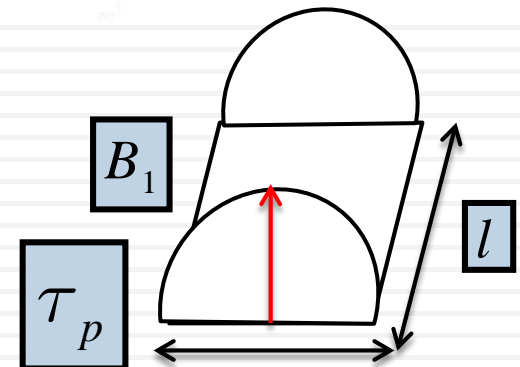
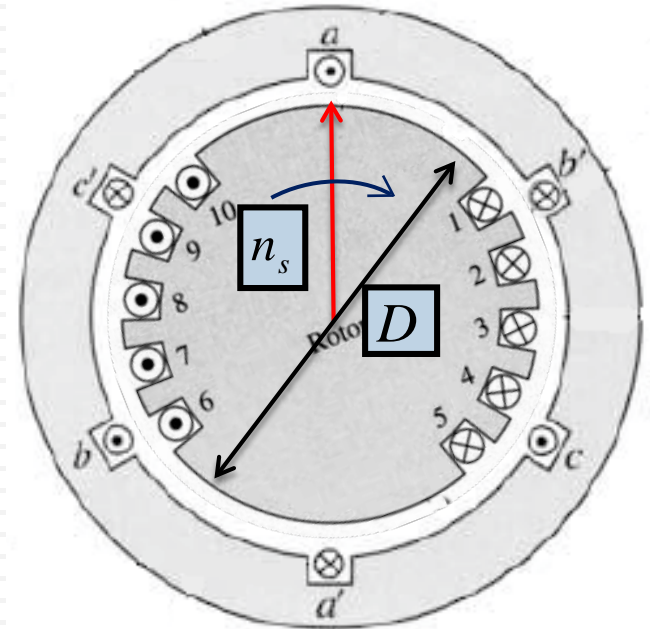
$$E_{1m} = B_1 l v = \frac{\phi p}{D} \times \frac{\pi f D}{p}$$

$$E_{1m} = \pi f \phi$$

$$E_{1rms} = \frac{\pi}{\sqrt{2}} f \phi$$

$$E_{1rms} = 2.22 f \phi$$

For one conductor

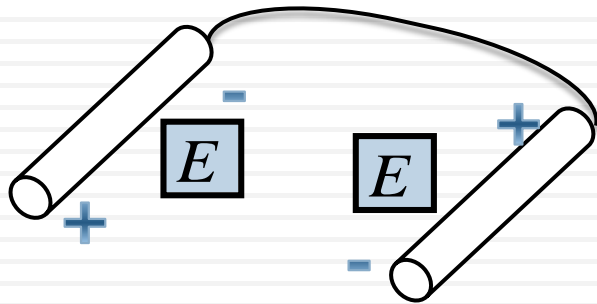


Generated Voltage (EMF)

8

Synchronous Machines

For One Turn



θ_s = turn span (pitch) angle

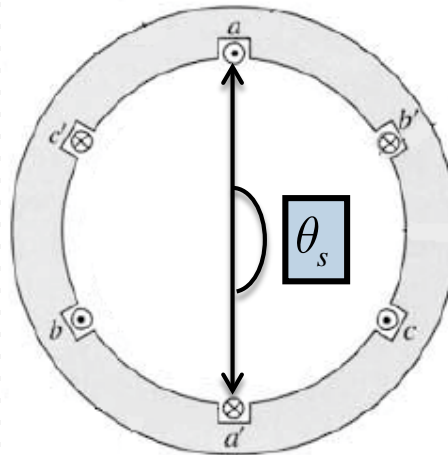
θ_c = turn chording angle

Chording Factor

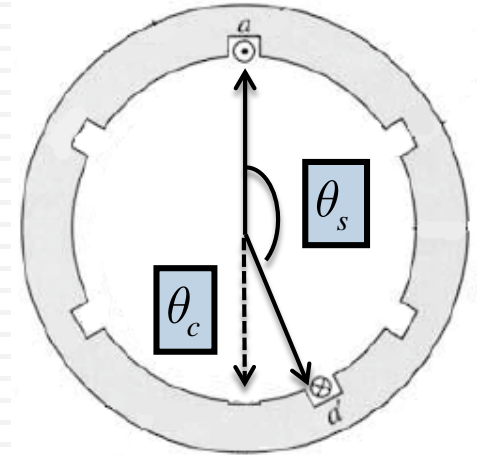
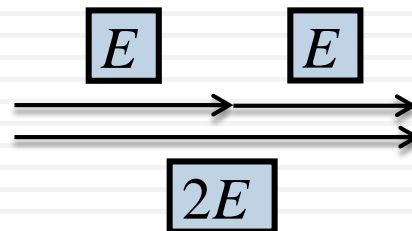
$$k_c = \frac{\text{vector sum}}{\text{arithmetic sum}}$$

$$k_c = \sin \frac{\theta_s}{2} = \cos \frac{\theta_c}{2}$$

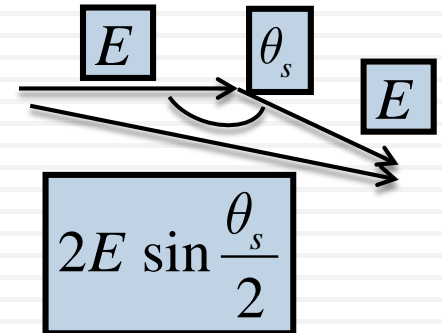
$$E_{turn} = 2 * E_{cond} * k_c$$



Full Pitched Turn



Chorded Turn



θ_s, θ_c in electrical degrees

$$E_{turn} = 4.44f \phi k_c$$

Generated Voltage (EMF)

9

Synchronous Machines

For One Coil

N_c = number of turns per coil

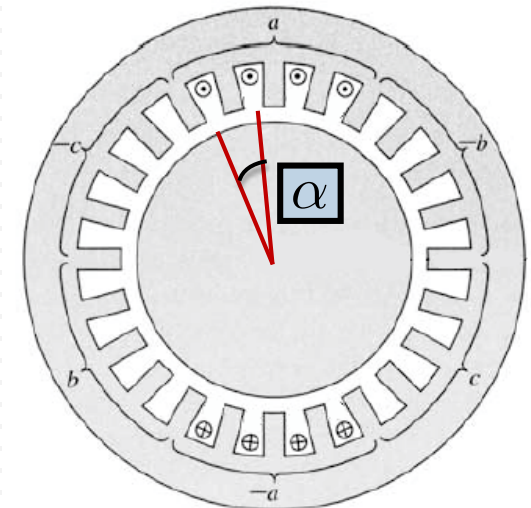
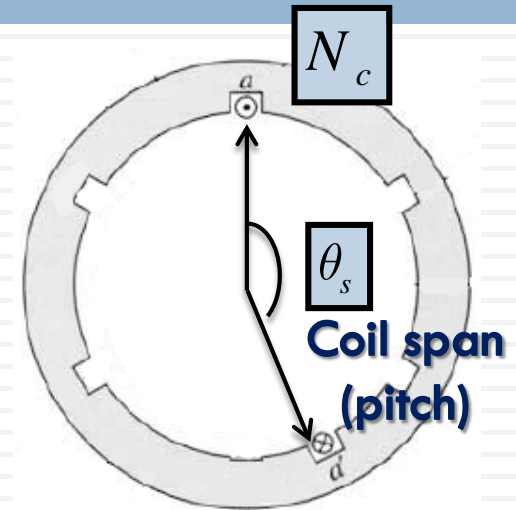
$$E_{coil} = 4.44f \phi k_c N_c$$

For One Coil Group

s = number of stator slots

$$q = \frac{s}{2p * 3}$$
 number of slots/pole/phase

q = number of coils/coil group

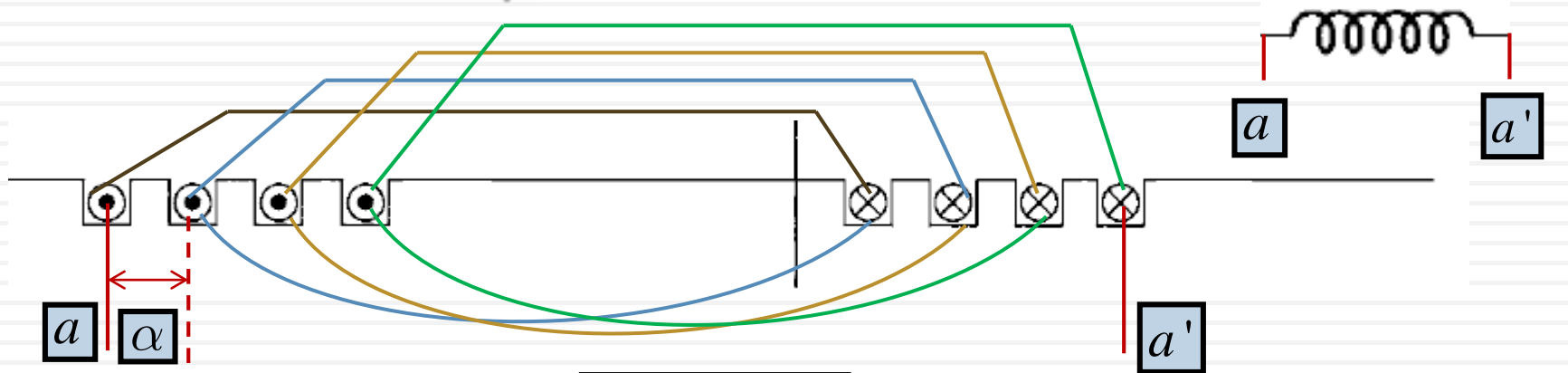


Generated Voltage (EMF)

10

Synchronous Machines

For One Coil Group



$\alpha = \text{slot angle (pitch)}$

$$\alpha = \frac{360}{s} p \quad \alpha \text{ in electrical degrees}$$

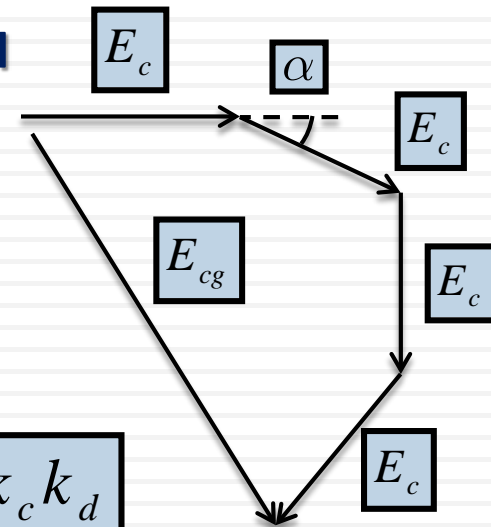
Distribution (Pitch) Factor

$$k_d = \frac{\text{vector sum}}{\text{arithmetic sum}}$$

$$k_d = \frac{\sin(q \alpha / 2)}{q \sin(\alpha / 2)}$$

$$E_{\text{coil group}} = E_{\text{coil}} * q * k_d$$

$$E_{cg} = 4.44 f \phi q N_c k_c k_d$$

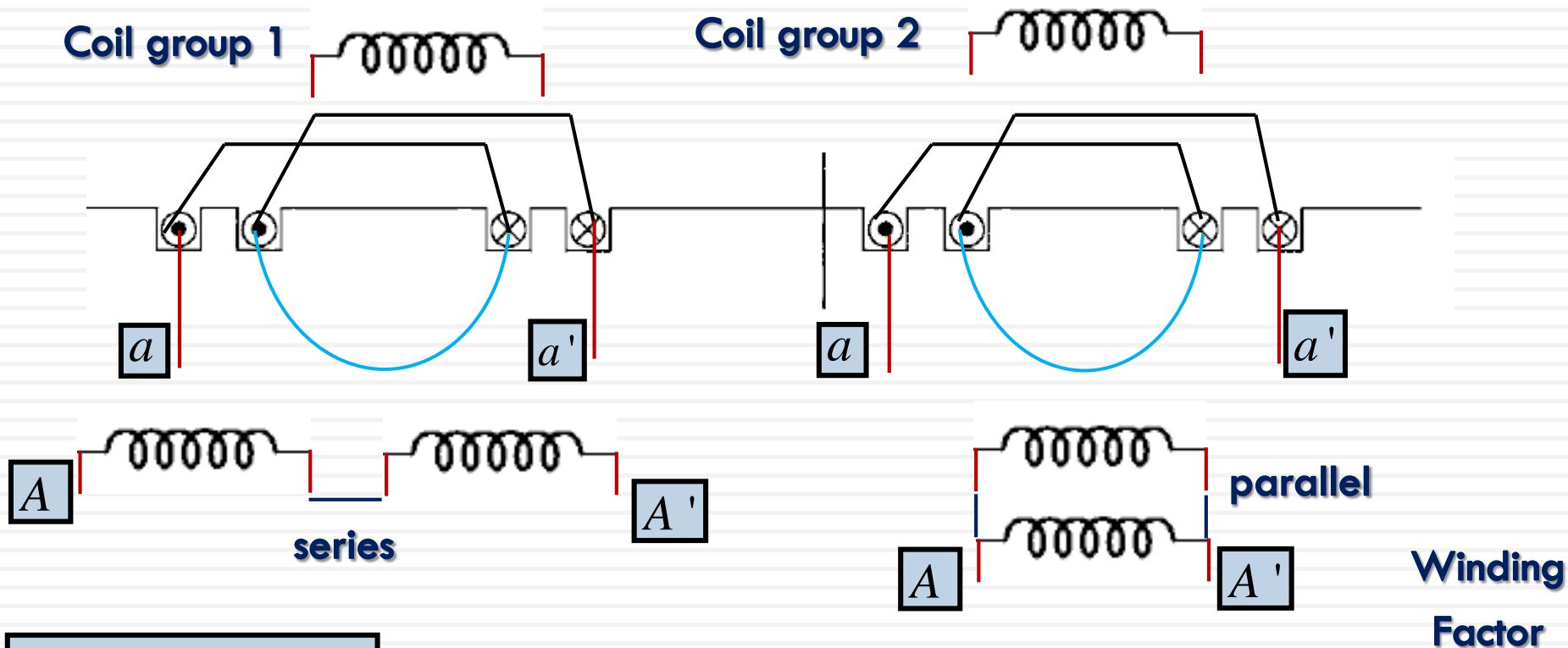


Generated Voltage (EMF)

11

Synchronous Machines

For One Phase



$$E_{phase} = E_{cg} \frac{G}{m}$$

$G = \text{no. of coil groups/phase}$

$m = \text{no. of parallel paths}$



$$E_{phase} = 4.44f \phi q N_c G \frac{k_w}{m}$$

Winding Factor

Generated Voltage (EMF)

12

Synchronous Machines

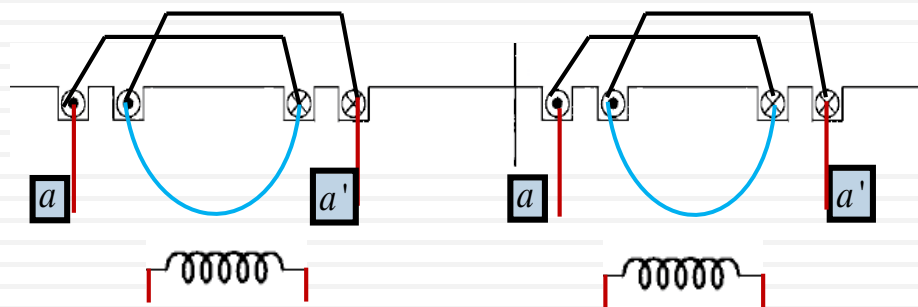
For One Phase



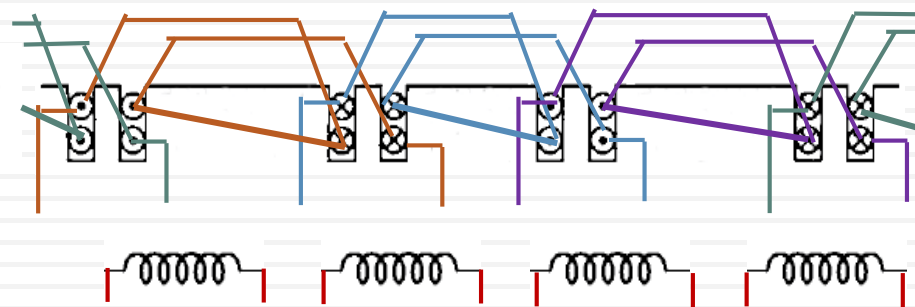
Single Layer



Double Layer



$$G = p$$



$$G = 2p$$

$c =$ no. of conductors/slot

$$c = N_c$$

$$c = 2N_c$$

Generated Voltage (EMF)

13

Synchronous Machines

For One Phase



Single Layer

$$G = p$$

$$c = N_c$$



Double Layer

$$G = 2p$$

$$c = 2N_c$$

$$E_{phase} = 4.44f \phi q N_c G \frac{k_w}{m}$$

$$E_{phase} = 4.44f \phi q c p \frac{k_w}{m}$$

$$E_{phase} = 4.44f \phi q \frac{c}{2} (2p) \frac{k_w}{m}$$

$$E_{phase} = 4.44f \phi (qcp) \frac{k_w}{m}$$

Generated Voltage (EMF)

14

Synchronous Machines

For One Phase

$$E_{phase} = 4.44f \phi(qcp) \frac{k_w}{m}$$

q = no. of slots/pole/phase

c = no. of conductors/slot

p = no. of per poles

$$N_{ph} = qcp$$

$$E_{phase} = 4.44f \phi N_{ph} \frac{k_w}{m}$$

Generated Voltage (EMF)

15

Synchronous Machines

For space harmonics

$$E_{1\text{phase}} = 4.44f \phi_1 N_{ph} \frac{k_{w1}}{m}$$

For any harmonic:

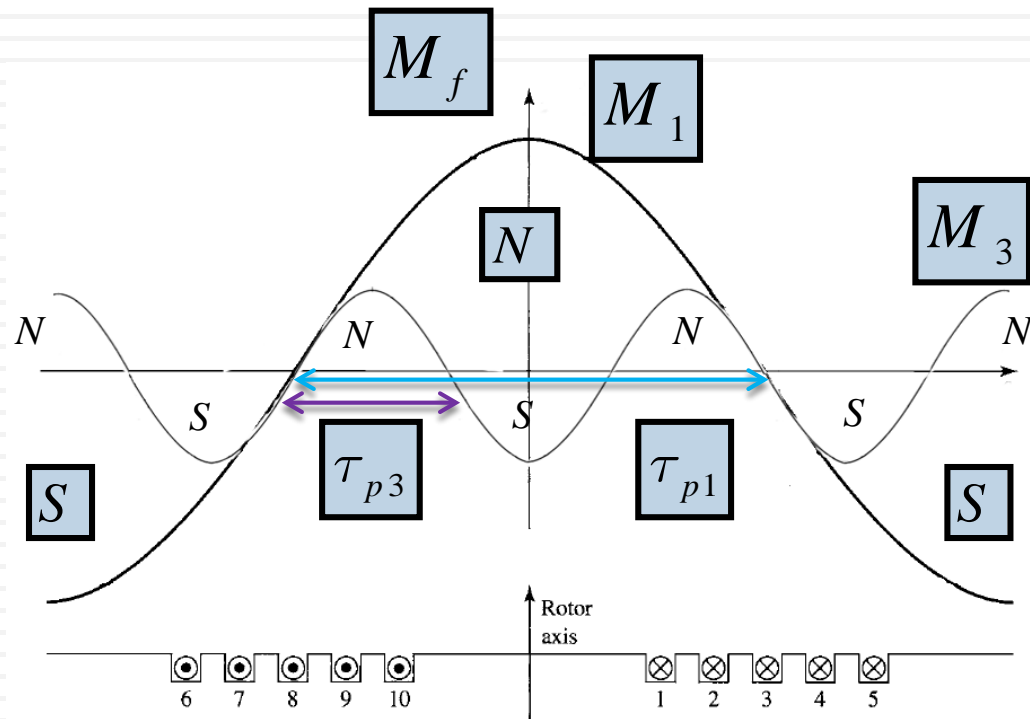
$$f_h = hf$$

$$\phi_h = \frac{2}{\pi} B_h \tau_{ph} l$$

$$k_{ch} = \sin \frac{h\theta_s}{2}$$

$$k_{dh} = \frac{\sin(hq \alpha/2)}{q \sin(h \alpha/2)}$$

$$\tau_{ph} = \frac{\tau_p}{h}$$



Generated Voltage (EMF)

17

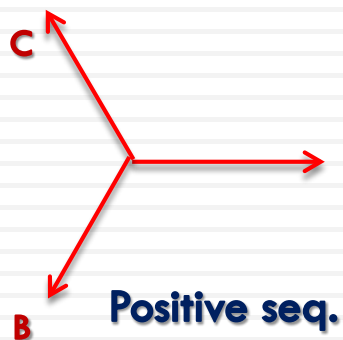
Synchronous Machines

For space harmonics

$$e_{ah} = \sqrt{2}E_h \cos(h\omega_e t)$$

$$e_{bh} = \sqrt{2}E_h \cos(h(\omega_e t - 120))$$

$$e_{ch} = \sqrt{2}E_h \cos(h(\omega_e t + 120))$$

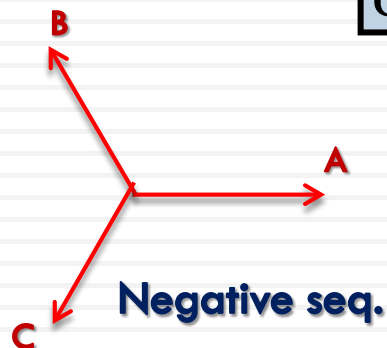


$h=1,7,13,\dots$

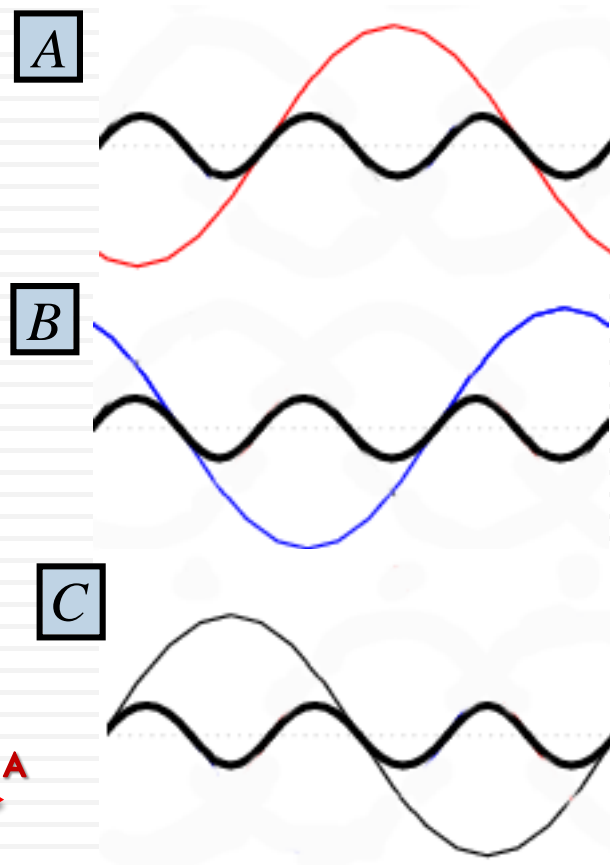


Zero seq.

$h=3,9,15,\dots$



$h=5,11,17,\dots$

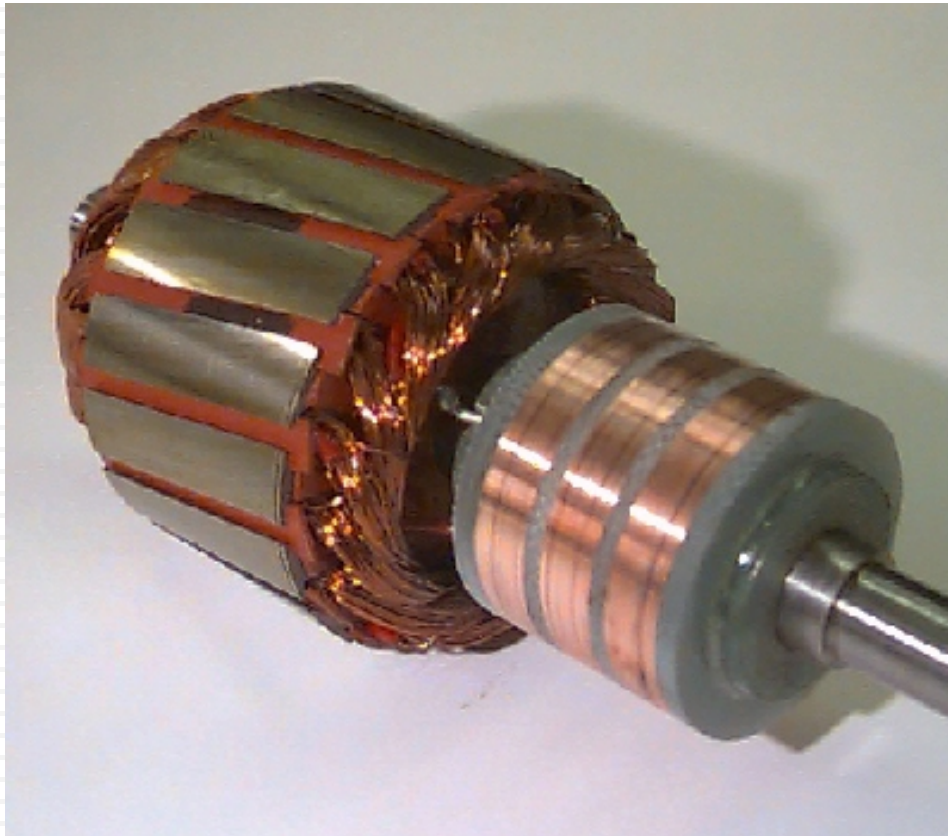


Generated Voltage (EMF)

18

Induction Machines

1. *Wound Rotor (Slip-Ring) Machine*

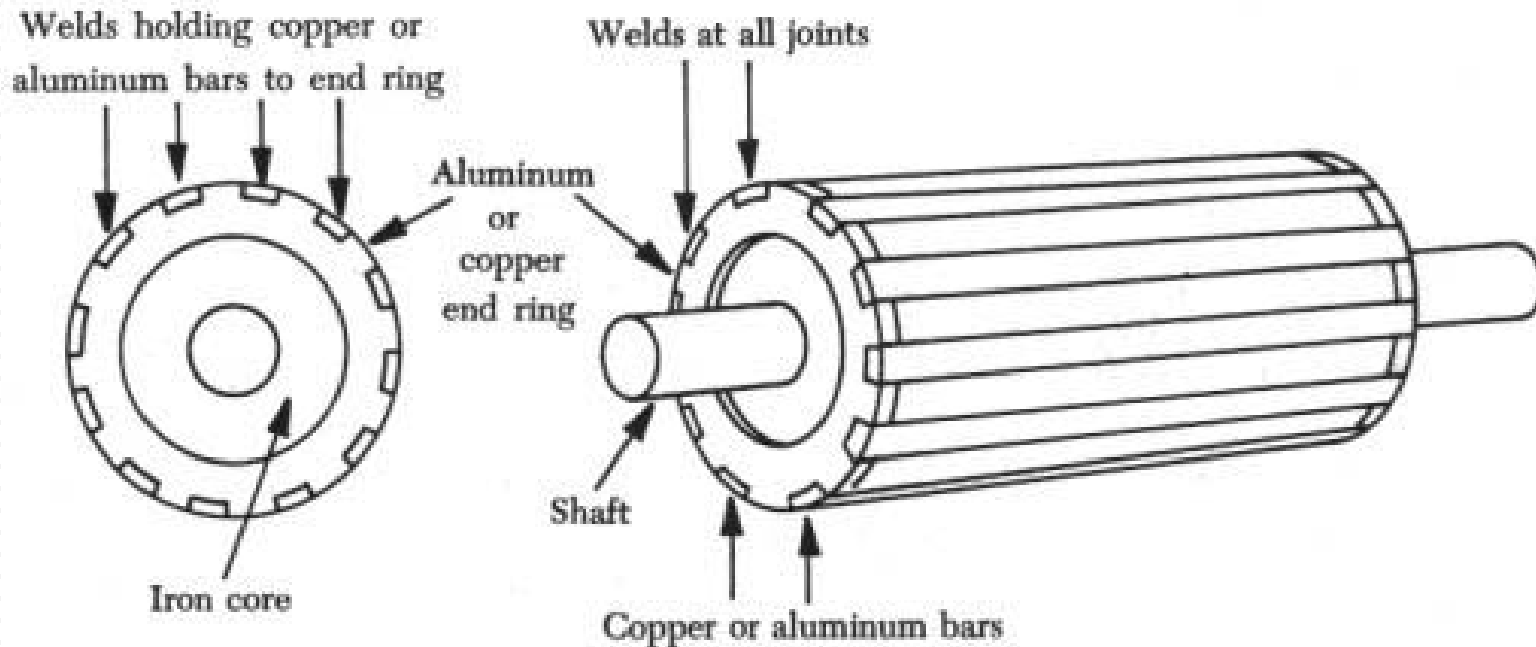


Generated Voltage (EMF)

20

Induction Machines

2. Squirrel Cage Rotor Machine

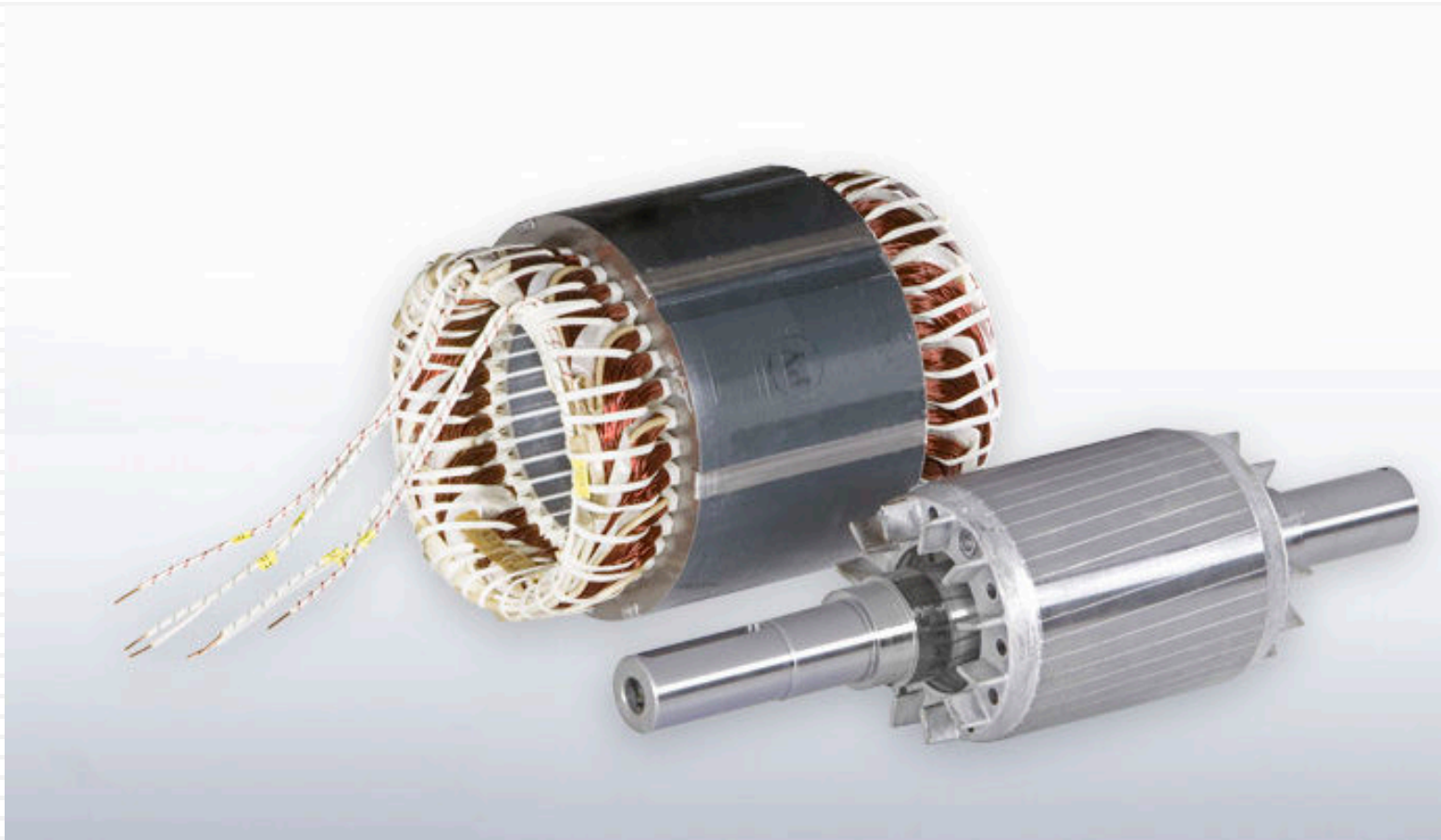


Generated Voltage (EMF)

21

Induction Machines

2. Squirrel Cage Rotor Machine



Generated Voltage (EMF)

22

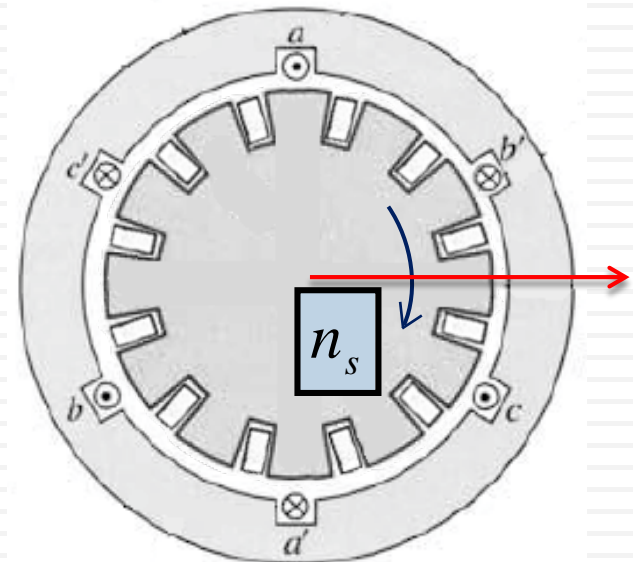
Induction Machines

2. Squirrel Cage Rotor Machine

$$E_{1 \text{ phase}} = 4.44f \phi N_1 \frac{k_{w1}}{m}$$

For simplicity, assume:

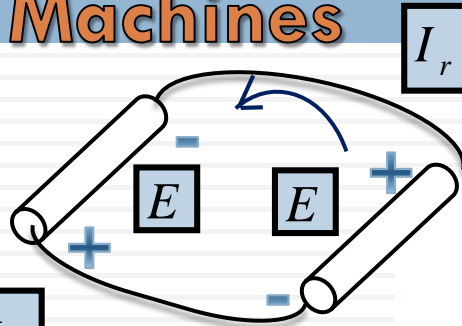
$$E_{2 \text{ phase}} = 4.44f \phi N_2 \frac{k_{w2}}{m}$$



Torque Production

23

Induction Machines



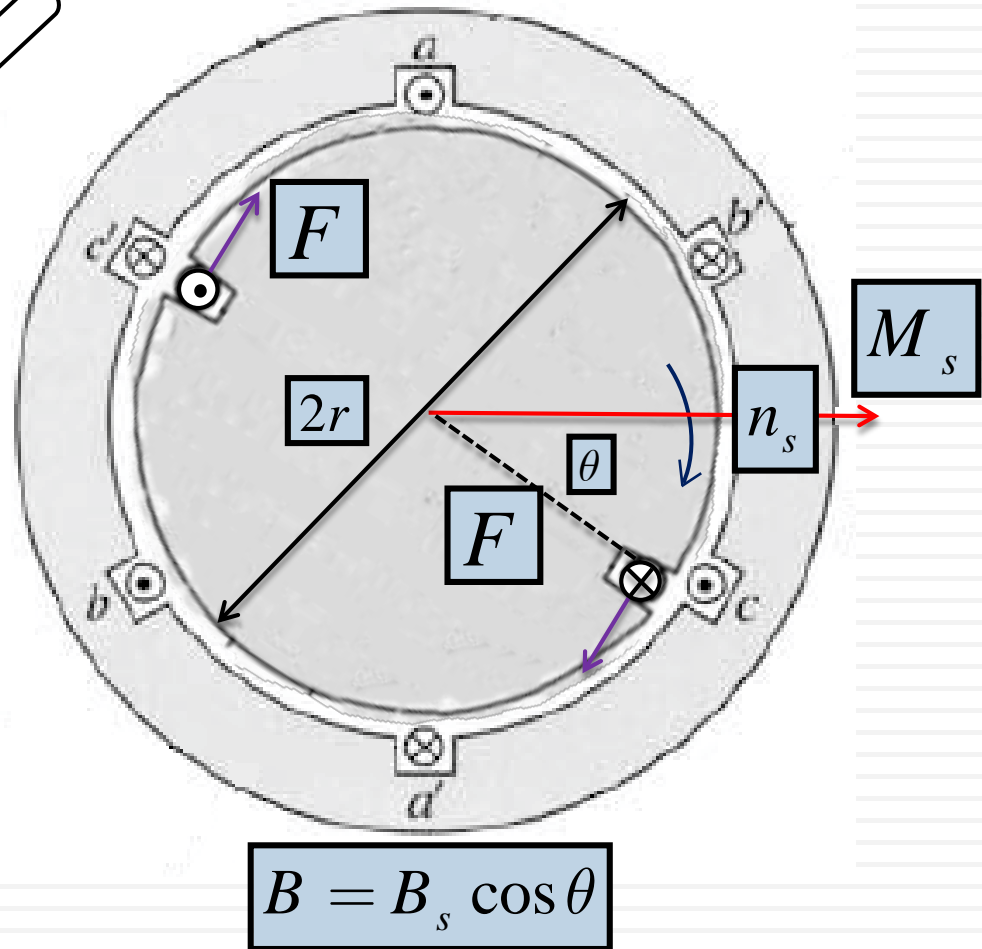
$$F = I_r BL$$

$$F = I_r LB_s \cos \theta$$

$$T = \underline{r} \times \underline{F}$$

$$T = F(2r)$$

$$T = 2rI_r LB_s \cos \theta$$



Torque Production

24

Induction Machines

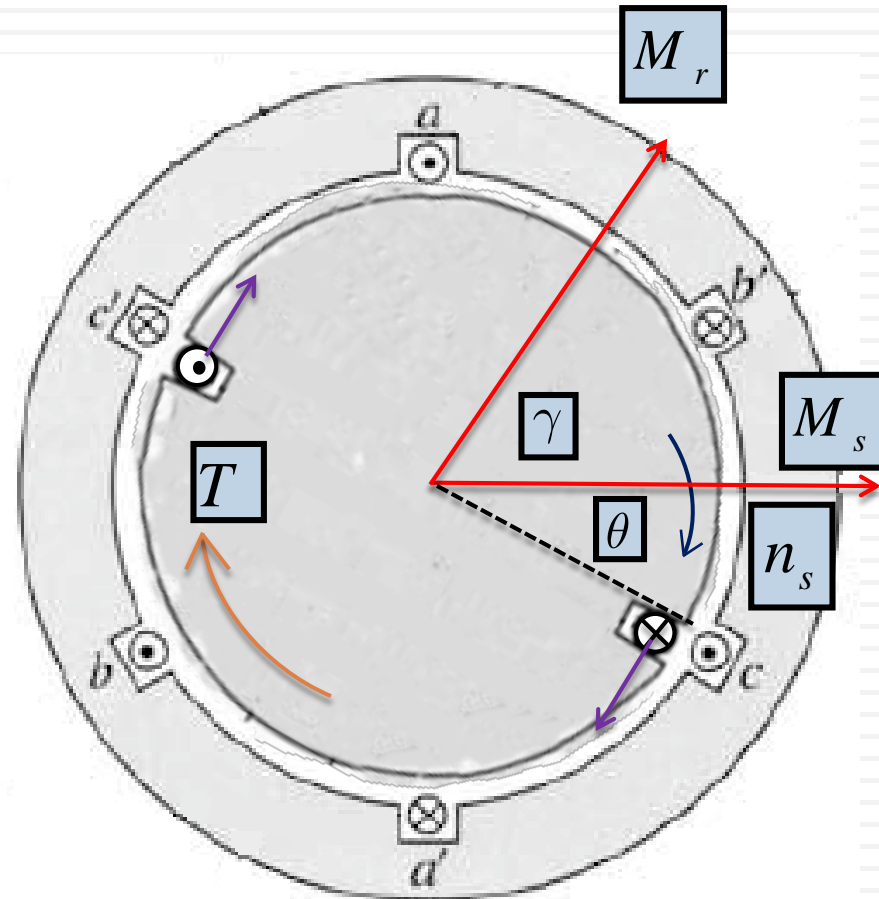
$$B_r \propto I_r$$

$$T = k B_s B_r \cos \theta$$

$$\gamma = 90 - \theta$$

$$T = k B_s B_r \sin \gamma$$

$$T = k \hat{B}_s \times \hat{B}_r$$



$$B = B_s \cos \theta$$