# Electric Machinery II

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Text: A. E. Fitzgerald, Charles Kingsley, Jr And Stephen D. Umans, *Electric Machinery*. Mc GrawHill, 7th Edition

# Electrical Machine II Syllabus

1. Introduction

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2. Introduction to Rotating Machines
   - Voltage Generation in Electrical Machinery
     - AC Machines
     - DC Machines
   - Force and Torque in Electrical Machines
     - Electromechanical Energy-Conversion Principles
     - Determination of Magnetic Torques Through Magnetic Field View Point
     - Torque Production Condition
     - Stator Magnetic Field in DC and AC Machines

3. DC Machines

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4. Induction Machines

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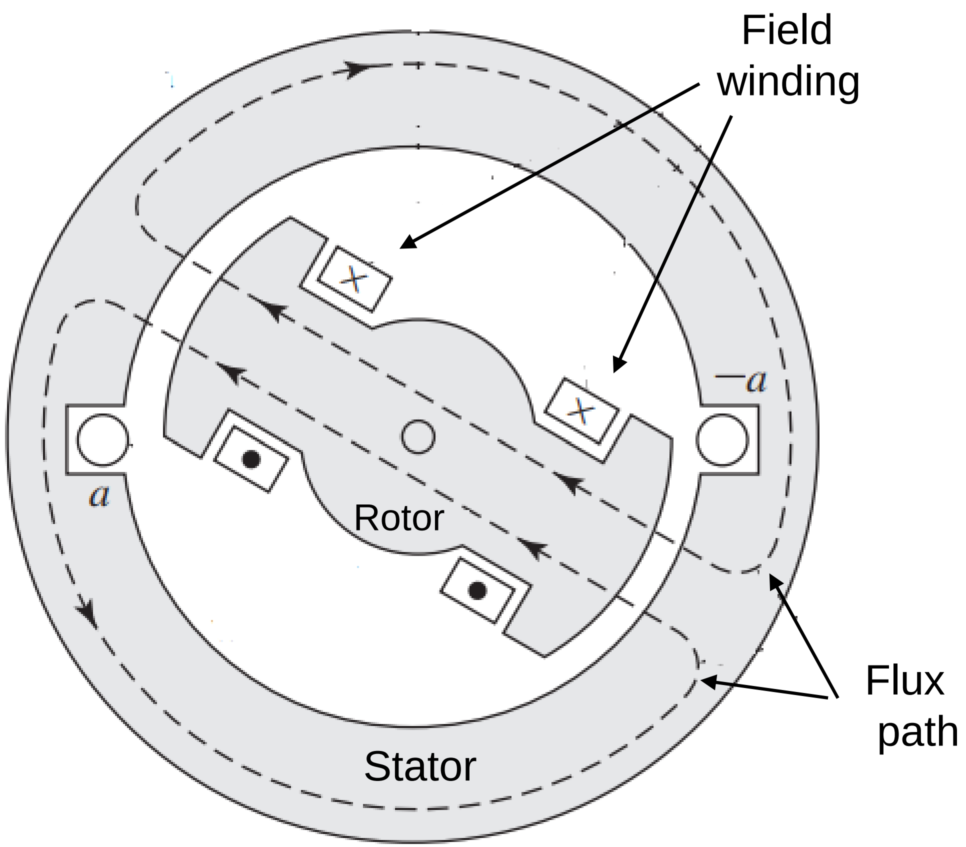
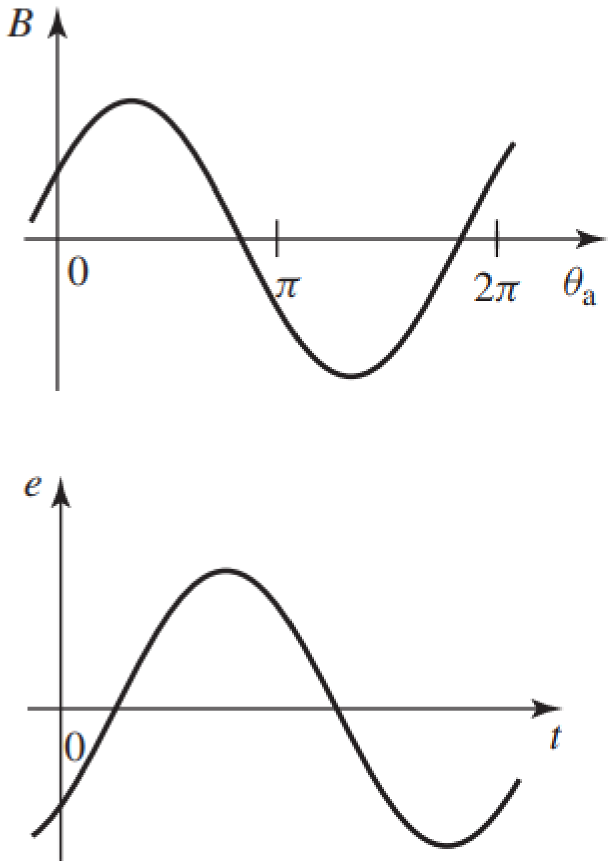
# Voltage Generation in Electrical Machinery

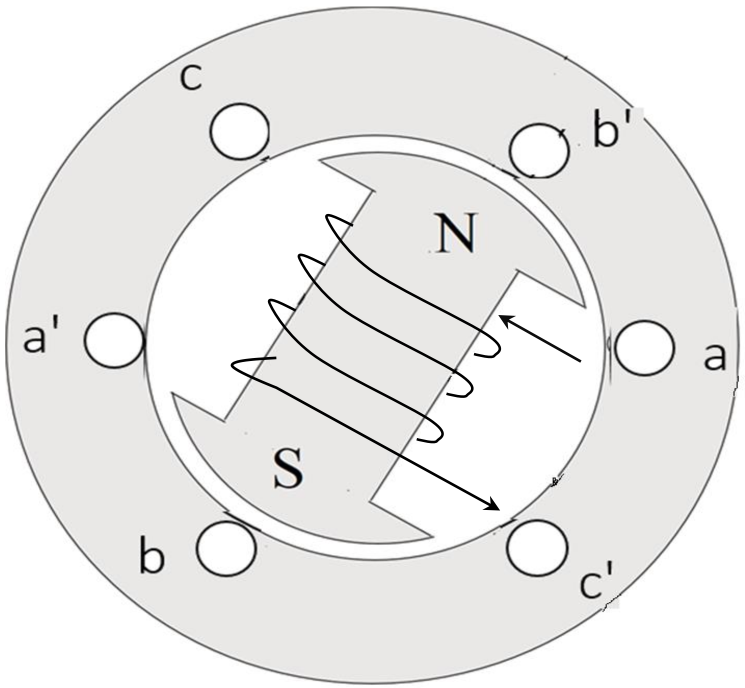
## AC Machines (Two poles one phase)
## Salient pole

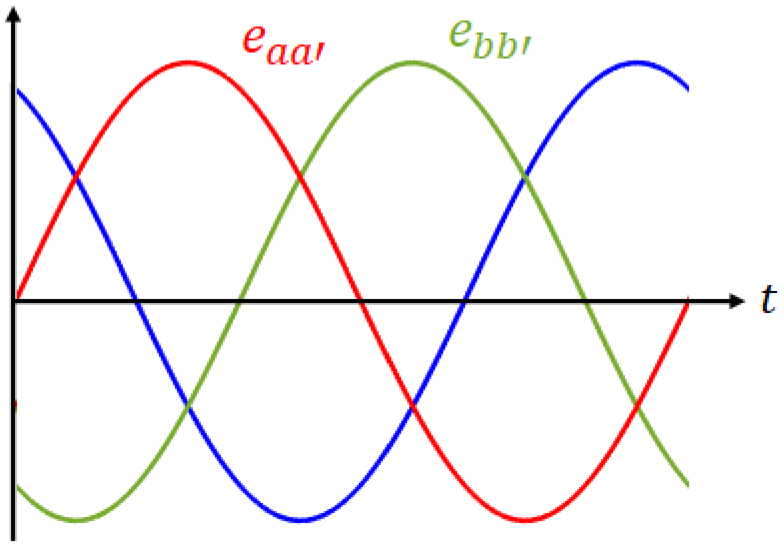


# Voltage Generation in Electrical Machinery

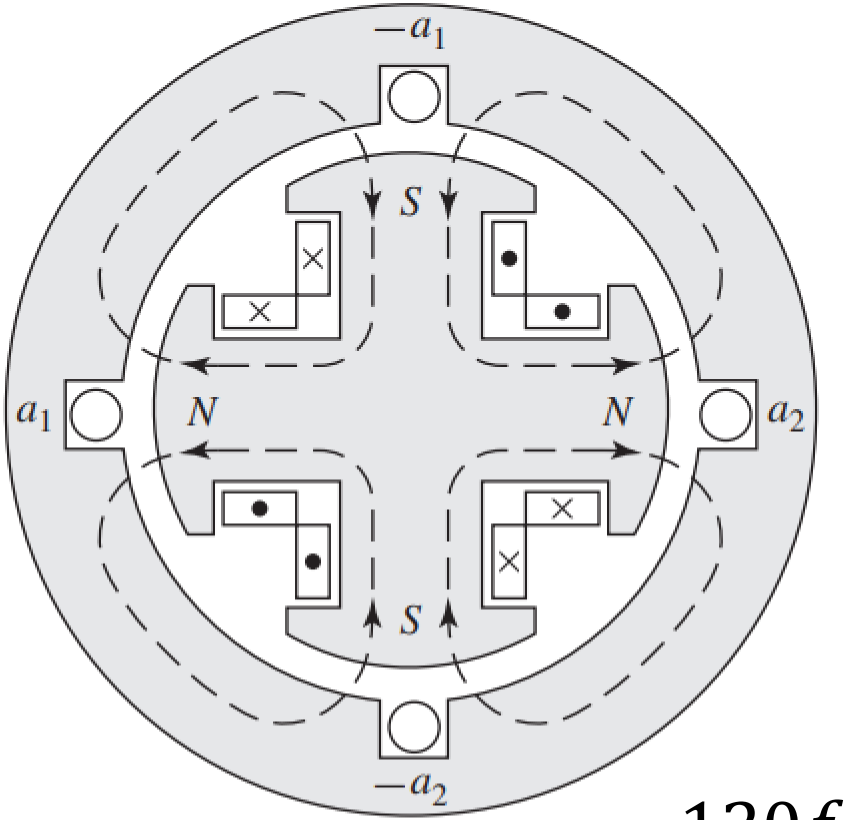
## AC Machines
## (Two poles three phases)
## Silent pole

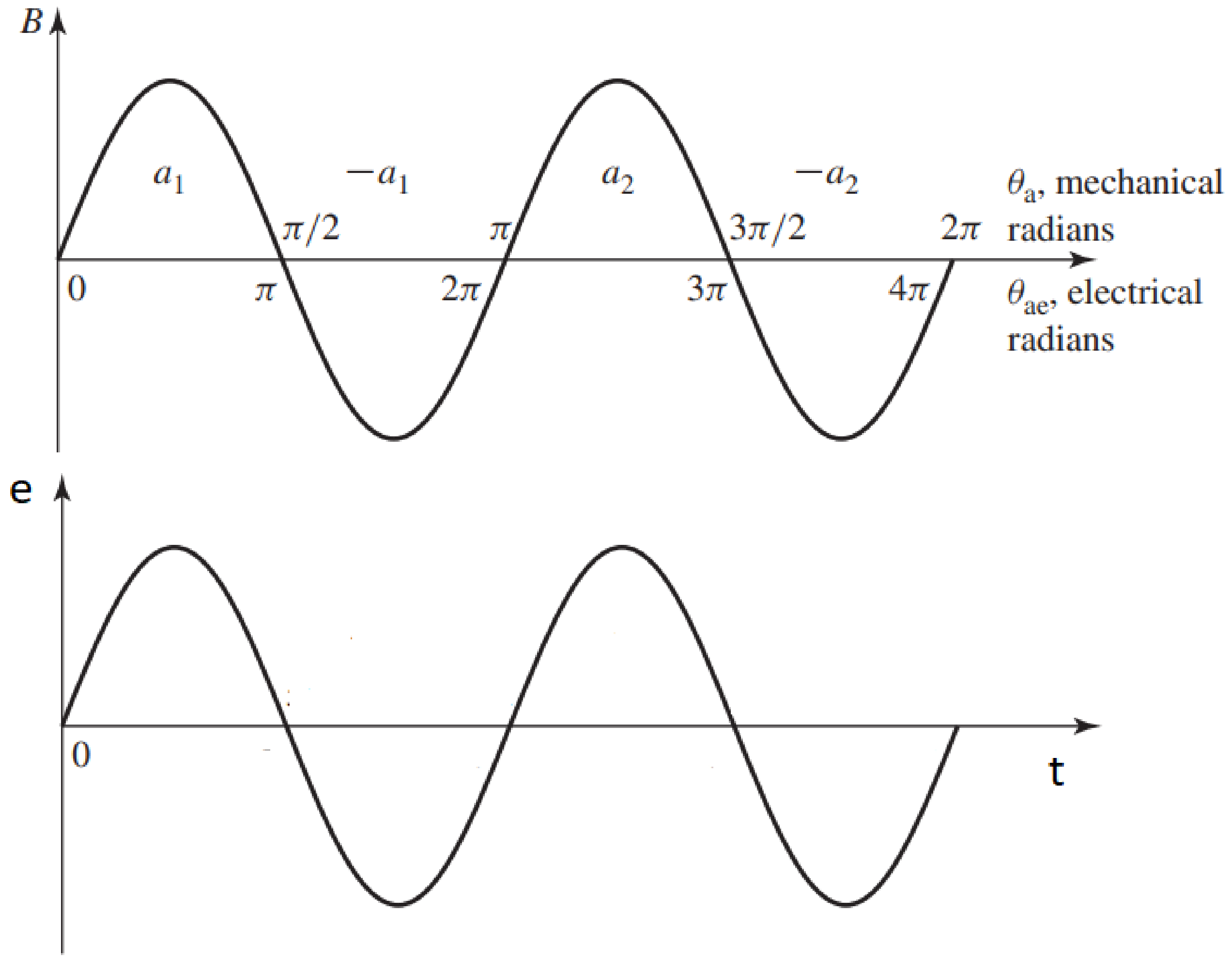


# Voltage Generation in Electrical Machinery

## AC Machines (Four poles one phase)
## Silent pole

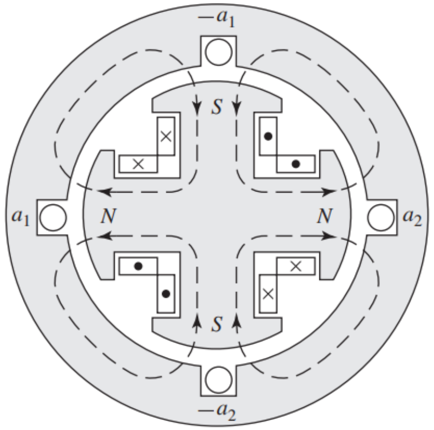


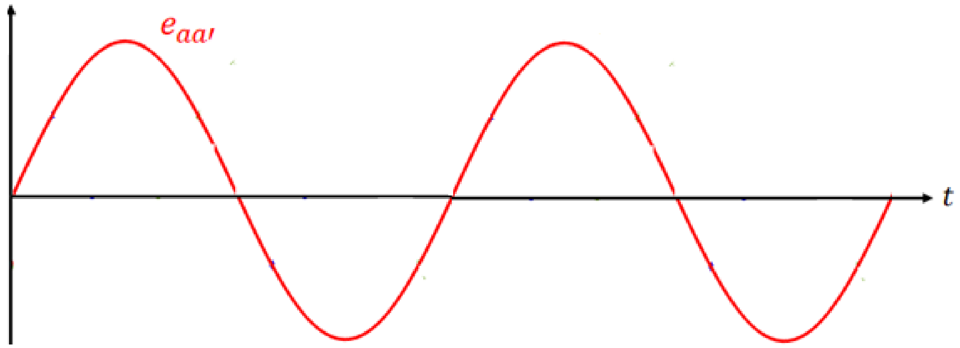




$$n = \frac{120f}{p}$$

$$f = \frac{pn}{120}$$

# Voltage Generation in Electrical Machinery




| | P=2 | P=4 | P=6 | P=8 | P=10 | P=12 |
|---|---|---|---|---|---|---|
| f=50 Hz | 3000 rpm | 1500 rpm | 1000 rpm | 750 rpm | ?? rpm | ?? rpm |
| f=60 Hz | 3600 rpm | 1800 rpm | 1200 rpm | 900 rpm | ?? rpm | ?? rpm |

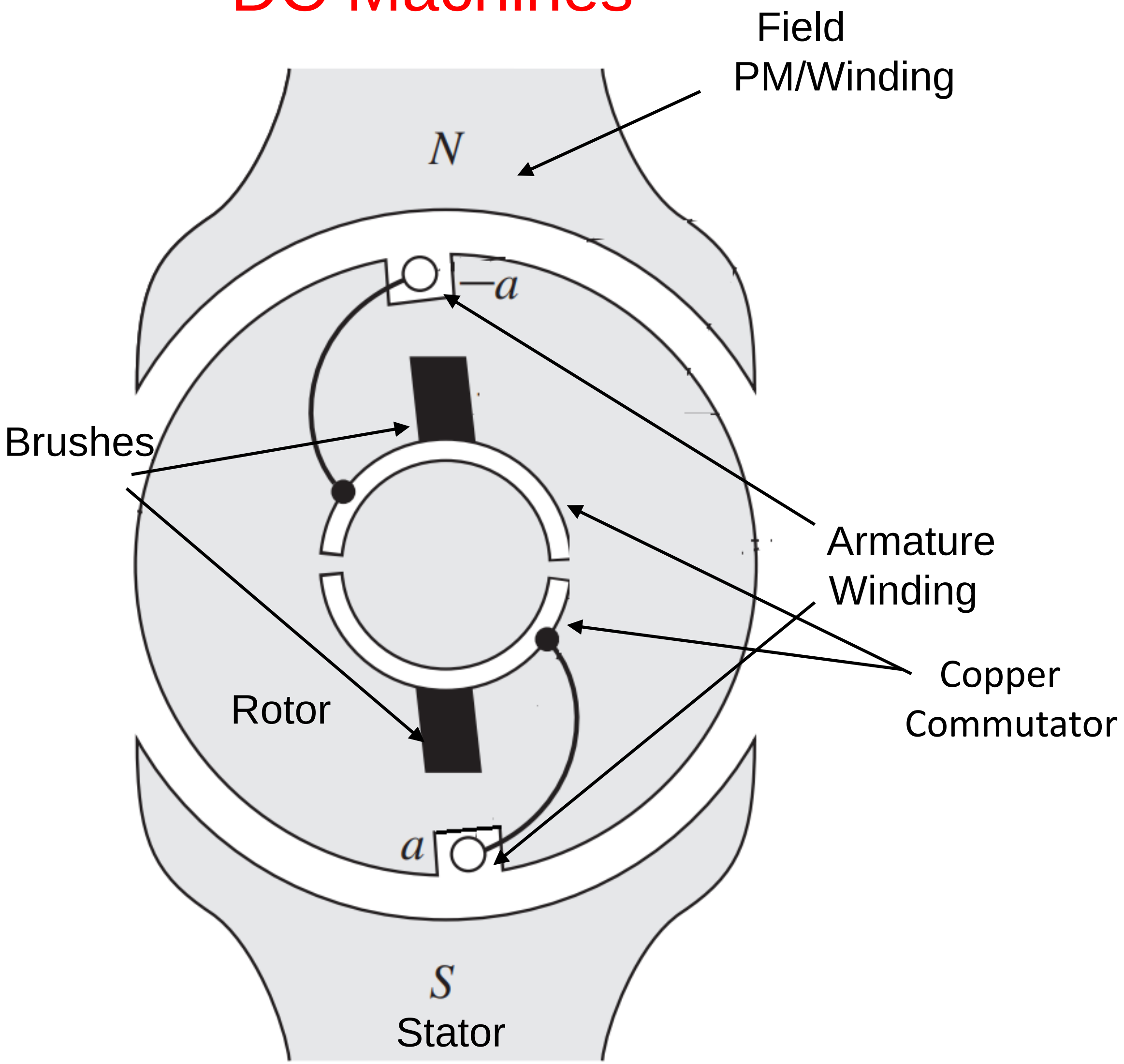
$$n = \frac{120f}{p}$$

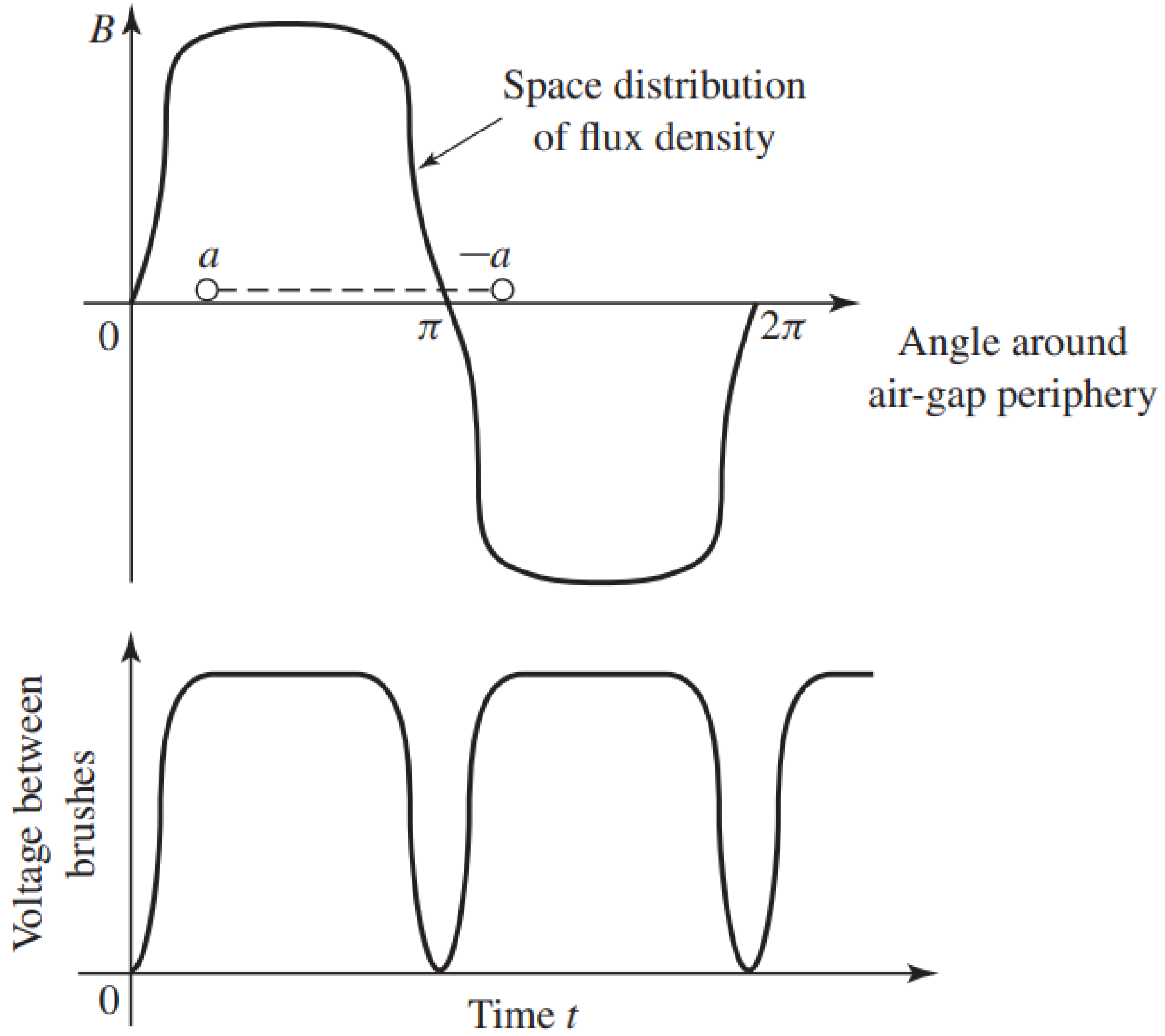
$$f = \frac{pn}{120}$$

Rotor and stator of a 90 MW, 22-pole hydro generator at the Dez Power Plant, Dezfool, Iran.

# Voltage Generation in Electrical Machinery

## DC Machines



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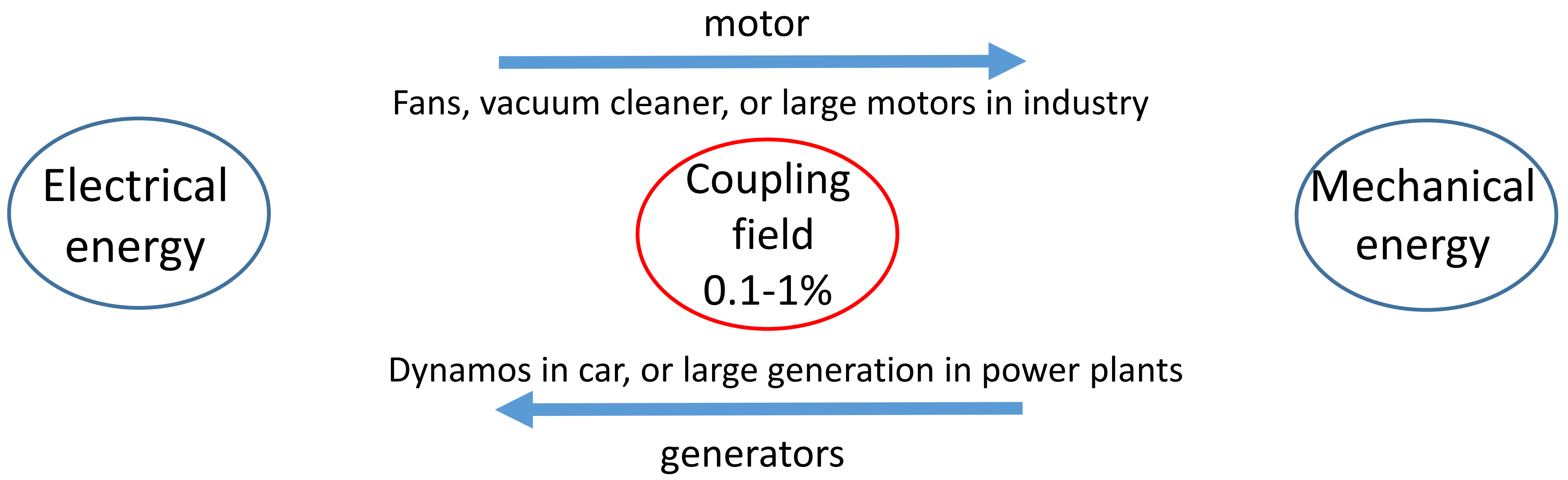
# Electromechanical Energy Conversion Principles



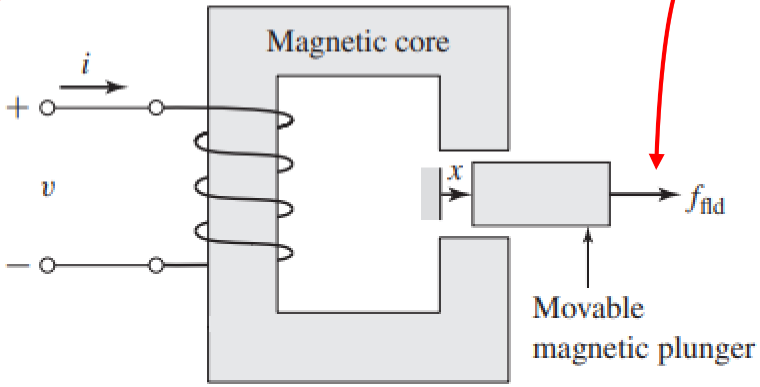

The technique for calculating forces and torques in the electromechanical-energy conversion process is known as the energy method and is based on the principle of conservation of energy

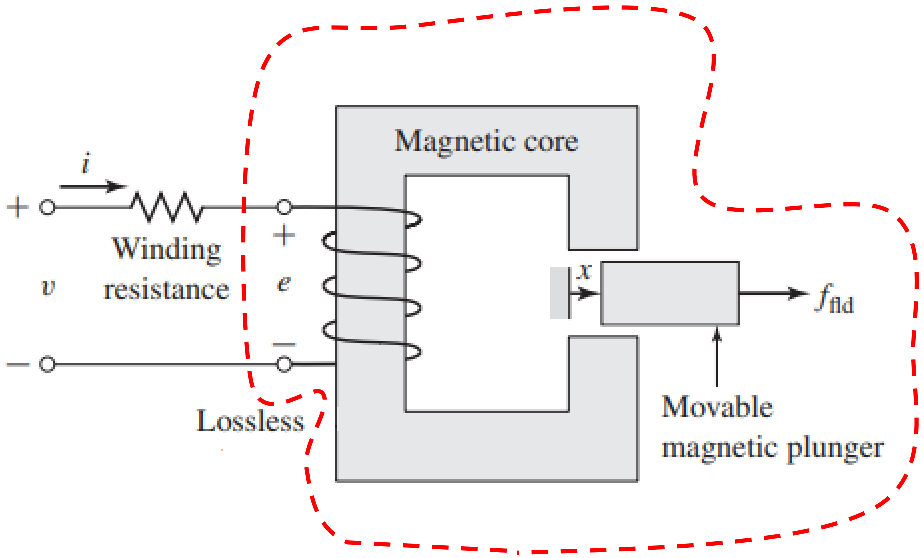
$$\begin{pmatrix}\text{Energy input}\\ \text{from electric}\\ \text{sources}\end{pmatrix} = \begin{pmatrix}\text{Mechanical}\\ \text{energy}\\ \text{output}\end{pmatrix} + \begin{pmatrix}\text{Increase in energy}\\ \text{stored in magnetic}\\ \text{field}\end{pmatrix} + \begin{pmatrix}\text{Energy}\\ \text{converted}\\ \text{into heat}\end{pmatrix}$$

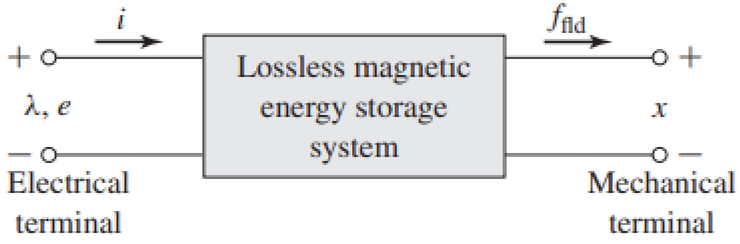
# Electromechanical Energy Conversion Principles

(Energy input from electric sources) = (Mechanical energy output) + (Increase in energy stored in magnetic field) + (Energy converted into heat)

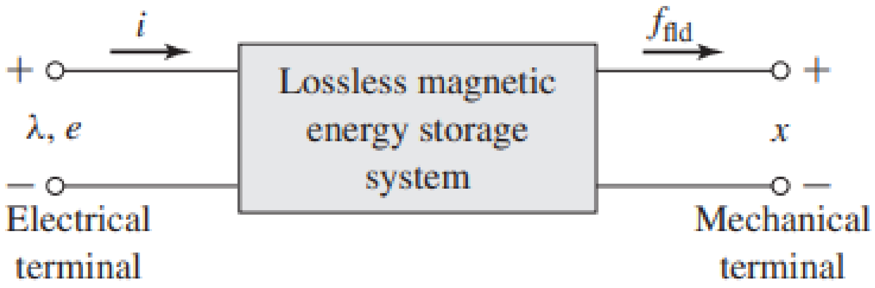
?? ??



# Electromechanical Energy Conversion Principles




$$\begin{pmatrix}\text{Energy input}\\ \text{from electric}\\ \text{sources}\end{pmatrix} = \begin{pmatrix}\text{Mechanical}\\ \text{energy}\\ \text{output}\end{pmatrix} + \begin{pmatrix}\text{Increase in energy}\\ \text{stored in magnetic}\\ \text{field}\end{pmatrix}$$

$$w_{ele} = w_{mec} + w_{fld}$$

$$\frac{dw_{ele}}{dt} = \frac{dw_{mec}}{dt} + \frac{dw_{fld}}{dt}$$

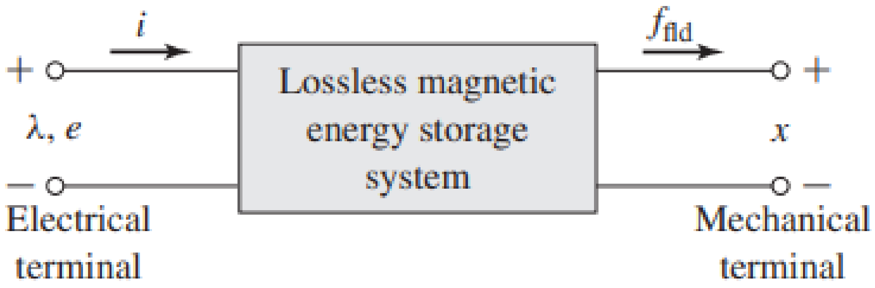
$$P_{ele} = P_{mec} + \frac{dw_{fld}}{dt}$$

$$f_{int}\frac{dx}{dt} \quad or \quad \tau_{int}\frac{d\theta}{dt}$$

$$ei$$

$$\frac{dw_{fld}}{dt} = P_{ele} - P_{mec}$$

# Electromechanical Energy Conversion Principles




$$\begin{pmatrix}\text{Energy input}\\ \text{from electric}\\ \text{sources}\end{pmatrix} = \begin{pmatrix}\text{Mechanical}\\ \text{energy}\\ \text{output}\end{pmatrix} + \begin{pmatrix}\text{Increase in energy}\\ \text{stored in magnetic}\\ \text{field}\end{pmatrix}$$

$$\frac{dw_{fld}}{dt} = P_{ele} - P_{mec}$$

$ei$ ; $f_{int}\frac{dx}{dt}$ or $\tau_{int}\frac{d\theta}{dt}$

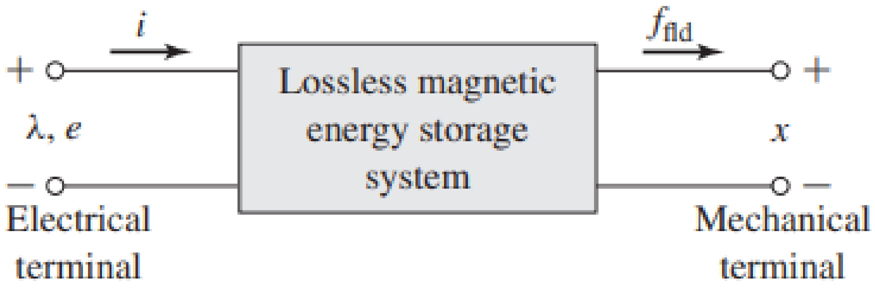
$$\frac{dw_{fld}}{dt} = i\frac{d\lambda}{dt} - f_{int}\frac{dx}{dt}$$

$$dw_{fld} = id\lambda - f_{int}dx$$

We know that $w_{fld}$ is a function of $\lambda$ and $x$ so its differential is:

$$dw_{fld}(\lambda, x) = \frac{\partial w_{fld}(\lambda, x)}{\partial \lambda}d\lambda + \frac{\partial w_{fld}(\lambda, x)}{\partial x}dx$$

# Electromechanical Energy Conversion Principles




$$dw_{fld} = i d\lambda - f_{int} dx$$

$$dw_{fld}(\lambda, x) = \frac{\partial w_{fld}(\lambda, x)}{\partial \lambda} d\lambda + \frac{\partial w_{fld}(\lambda, x)}{\partial x} dx$$

$$i = \frac{\partial w_{fld}(\lambda, x)}{\partial \lambda}$$

$$f_{int} = -\frac{\partial w_{fld}(\lambda, x)}{\partial x}$$

$$w_{fld}(\lambda, x) = ??$$

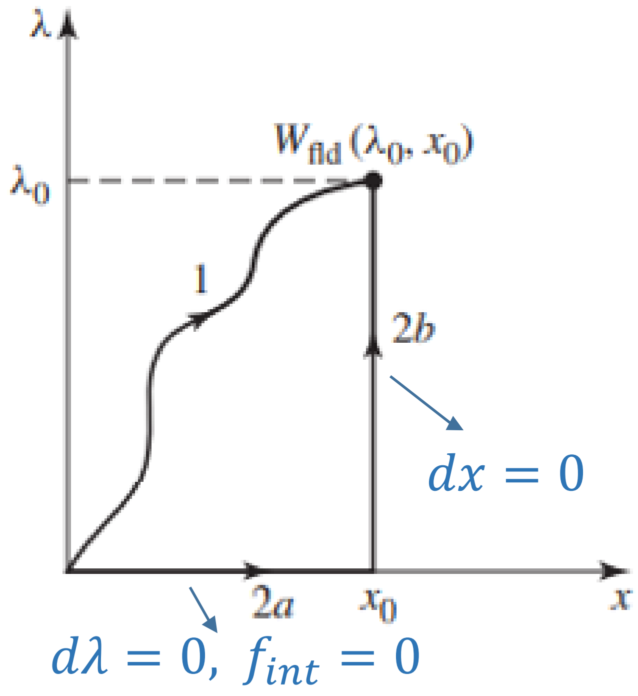
# Electromechanical Energy Conversion Principles

$$dw_{fld} = i d\lambda - f_{int} dx$$

$$w_{fld} = \int_0^{\lambda_0} i \, d\lambda = \frac{{\lambda_0}^2}{2L(x_0)}$$

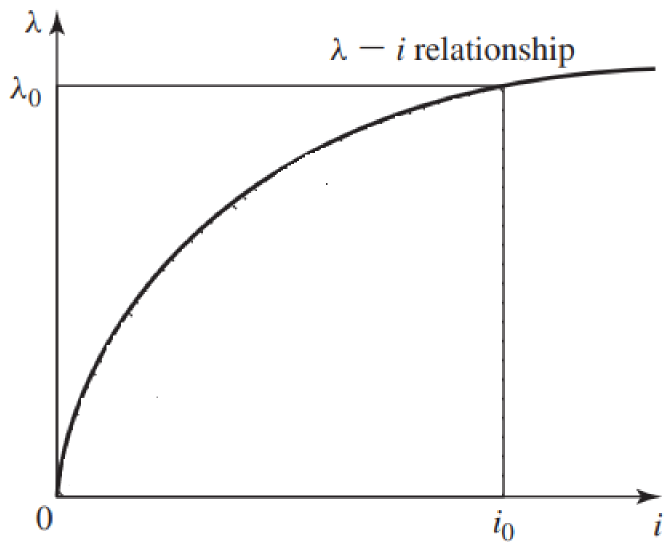
For linear system: $\frac{\lambda}{L}$

$$W_{fld} = \frac{\lambda^2}{2L(x)}$$




For nonlinear system:

$$w_{fld} = \int_0^{\lambda_0} i \, d\lambda$$



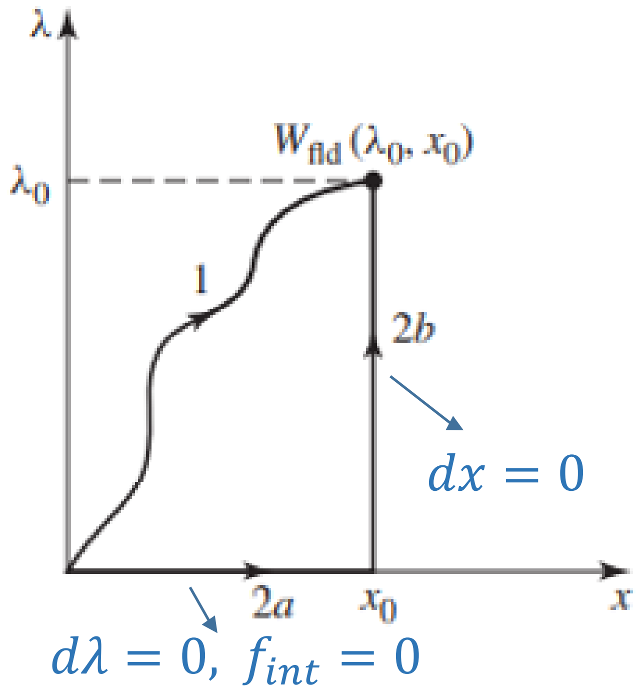
# Electromechanical Energy Conversion Principles

$$dw_{fld} = i d\lambda - f_{int} dx$$

$$w_{fld} = \int_0^{\lambda_0} i \, d\lambda = \frac{{\lambda_0}^2}{2L(x_0)}$$

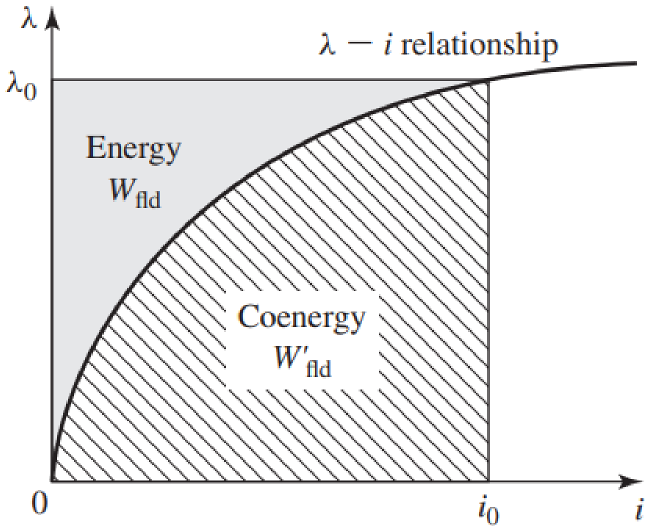
For linear system: $\frac{\lambda}{L}$

$$W_{fld} = \frac{\lambda^2}{2L(x)}$$



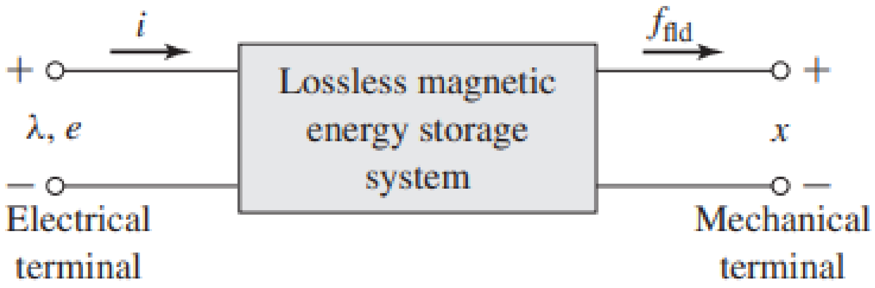

For nonlinear system:

$$w_{fld} = \int_0^{\lambda_0} i \, d\lambda$$




$$W'_{fld}(i, x) = i\lambda - W_{fld}(\lambda, x)$$

# Electromechanical Energy Conversion Principles




$$i = \frac{\partial w_{fld}(\lambda, x)}{\partial \lambda}$$

$$f_{int} = -\frac{\partial w_{fld}(\lambda, x)}{\partial x}$$

$$W_{fld} = \frac{\lambda^2}{2L(x)}$$

$$W_{fld} = \int_V \left(\frac{B^2}{2\mu}\right) dV$$

$$\tau_{int} = ??$$

Exercise 1: Show that

$$dw'_{fld} = \lambda di + f_{int} dx$$

Exercise 2: Show that

$$\lambda = \frac{\partial w'_{fld}(i, x)}{\partial i}$$

$$f_{int} = \frac{\partial w'_{fld}(i, x)}{\partial x}$$

$$W'_{fld} = \frac{1}{2} L(x) i^2$$

$$W'_{fld} = \int_V \frac{\mu H^2}{2} dV$$

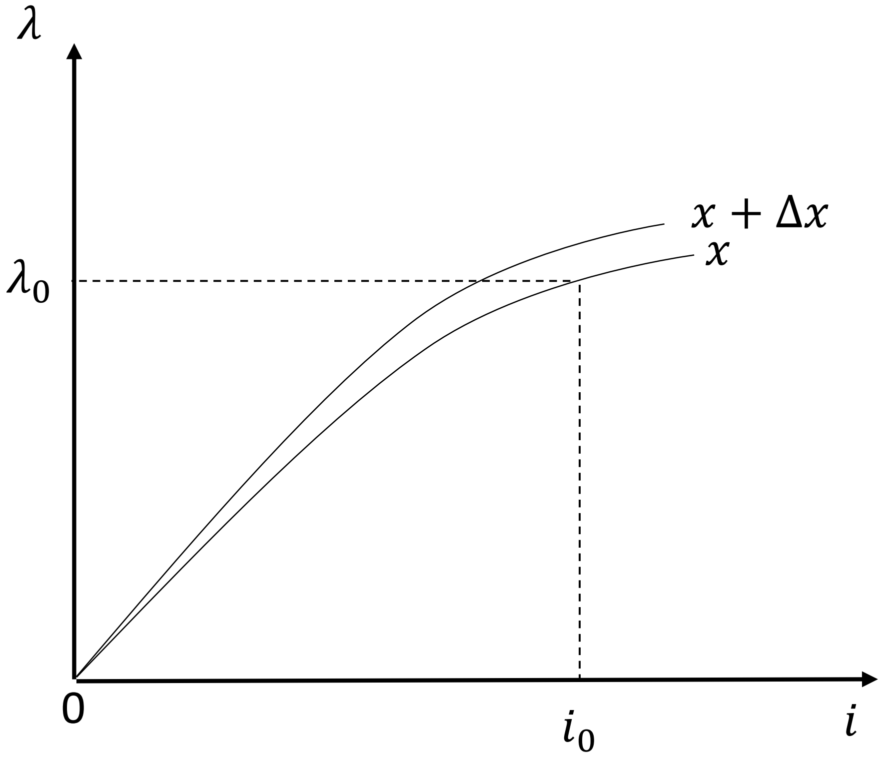
$$\tau_{int} = ??$$

# Electromechanical Energy Conversion Principles

$$f_{int} = -\frac{\partial w_{fld}(\lambda, x)}{\partial x}$$

$$f_{int} = \frac{\partial w'_{fld}(i, x)}{\partial x}$$

$w_{fld}(\lambda, x)$=?



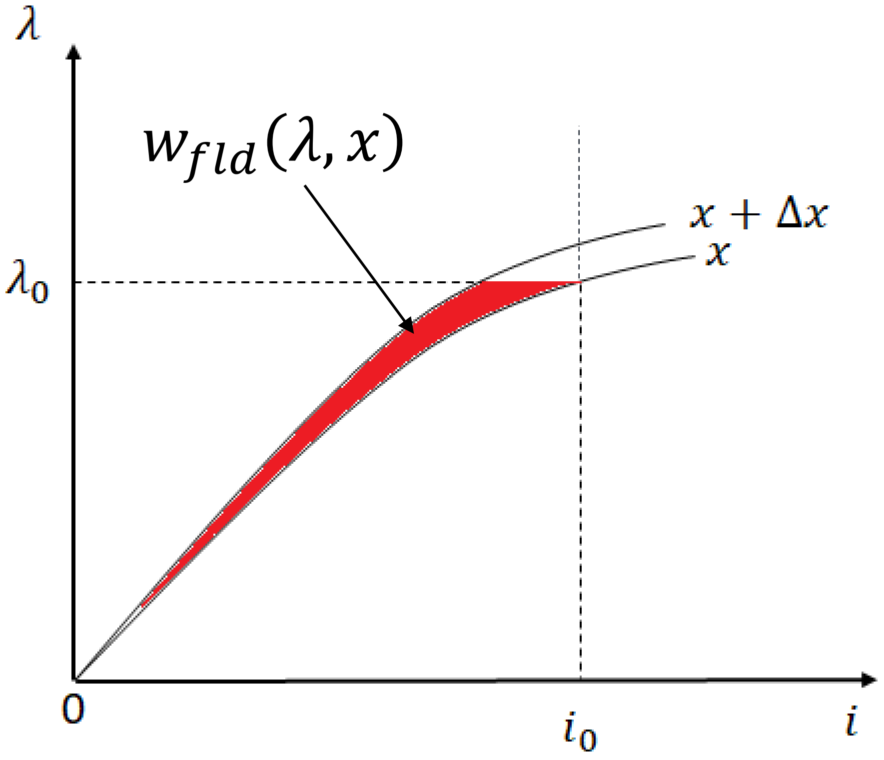
# Electromechanical Energy Conversion Principles

$$f_{int} = -\frac{\partial w_{fld}(\lambda, x)}{\partial x}$$

$w_{fld}(\lambda, x)$=?

$$f_{int} = \frac{\partial w'_{fld}(i, x)}{\partial x}$$

$w'_{fld}(i, x)$=?



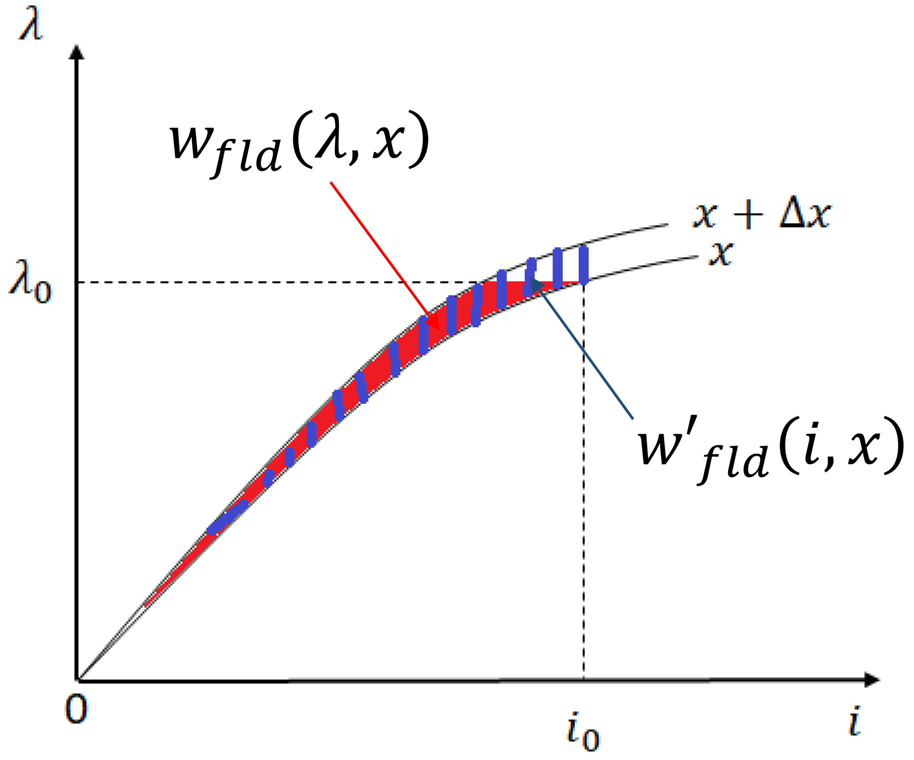
# Electromechanical Energy Conversion Principles

$$f_{int} = -\frac{\partial w_{fld}(\lambda, x)}{\partial x}$$

$w_{fld}(\lambda, x) = ?$

$$f_{int} = \frac{\partial w'_{fld}(i, x)}{\partial x}$$

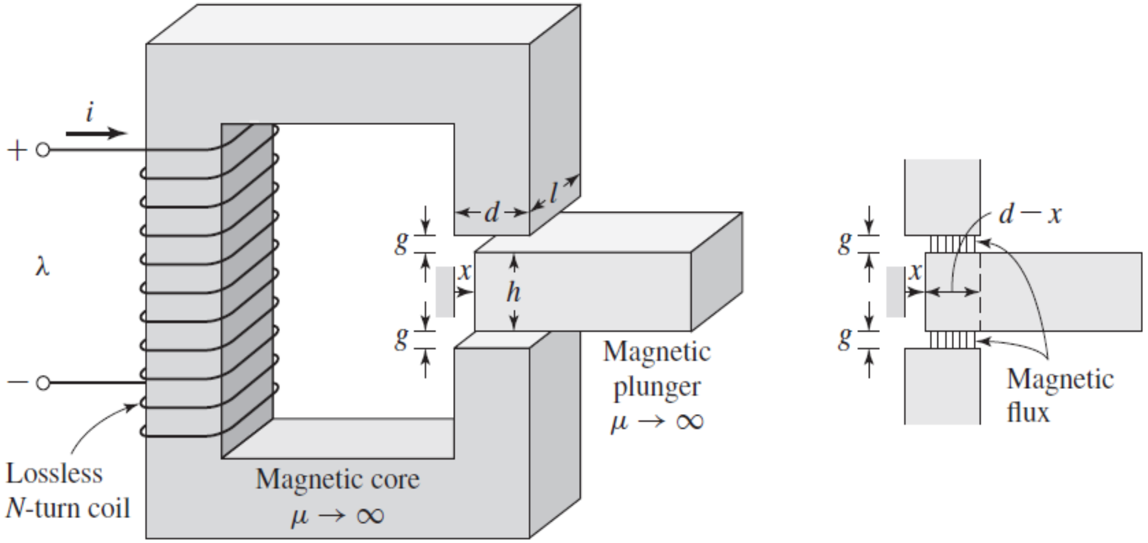
$w'_{fld}(i, x) = ?$



**Example 1:** In the figure below, assume the core is ideal and 0 < x ≪ d and h ≫ g.

**a:** Calculate the inductance of the coil.

$$L(x) = \frac{N^2}{R(x)}$$




$$R(x) = \frac{2g}{\mu_0 l(d-x)} \qquad L(x) = \frac{N^2 \mu_0 l(d-x)}{2g}$$

**b:** Determine the energy stored in the magnetic field of the system.

$$W_{fld} = \frac{1}{2L(x)}\lambda^2 \quad = \frac{\lambda^2 g}{N^2 \mu_0 l(d-x)}$$

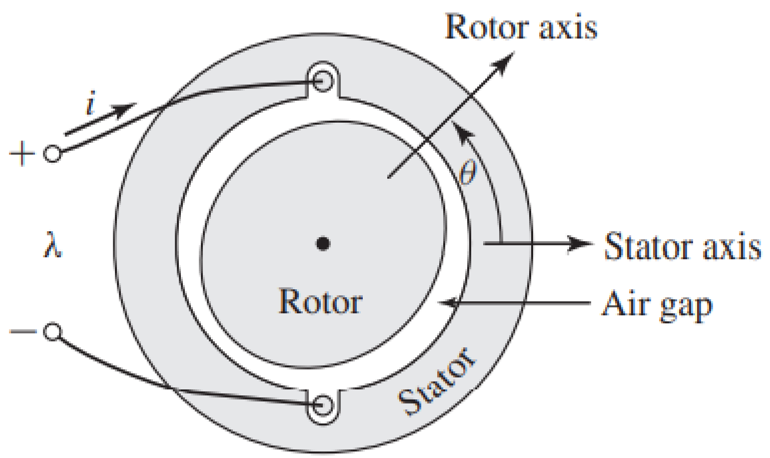
**c:** Find the force exerted on the moving part and its direction.

$$f_{int} = -\frac{\partial w_{fld}(\lambda, x)}{\partial x} \quad = -\frac{\lambda^2 g}{N^2 \mu_0 l(d-x)^2}$$

**d:** Determine the force exerted on the moving part using the co-energy method.

Example 2: The magnetic circuit of following figure consists of a single-coil stator and an oval rotor. Because the air-gap is nonuniform, the coil inductance varies with rotor angular position, measured between the magnetic axis of the stator coil and the major axis of the rotor, as

$$L(\theta) = L_0 + L_2 \cos(2\theta)$$




where $L_0$ = 10.6 mH and $L_2$ = 2.7 mH. Find the torque as a function of θ for a coil current of 2 A.

$$T_{fld}(\theta) = \frac{i^2}{2}\frac{dL(\theta)}{d\theta} = \frac{i^2}{2}\left(-2L_2 \sin(2\theta)\right)$$

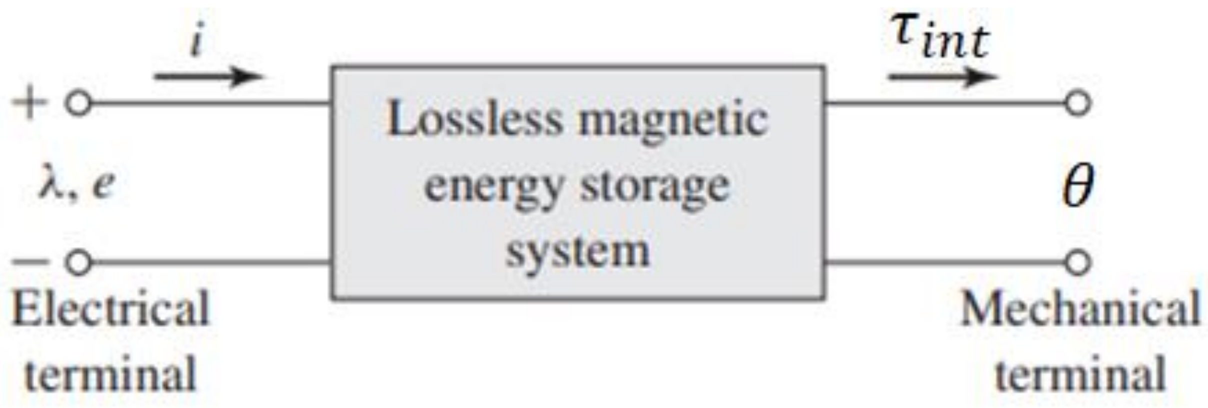
$$T_{fld}(\theta) = -(1.08 \times 10^{-2}) \sin(2\theta) \quad \mathrm{N \cdot m}$$

Exercise 1: Following table contains data from an experiment in which the inductance of a solenoid was measured as a function of position x, where x = 0 corresponds to the solenoid being fully retracted.

| $x$ [cm] | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $L$ [mH] | 2.8 | 2.26 | 1.78 | 1.52 | 1.34 | 1.26 | 1.20 | 1.16 | 1.13 | 1.11 | 1.10 |

Plot the solenoid force as a function of position for a current of 0.75 A over the range $0.2 \leq x \leq 1.8$ cm.

# Electromechanical Energy Conversion Principle




$$W_{fld} = \frac{\lambda^2}{2L(\theta)}$$

$$W_{fld} = \int_V \left(\frac{B^2}{2\mu}\right) dV$$

$$\tau_{int} = -\frac{\partial w_{fld}(B,\theta)}{\partial \theta}$$

$$\tau_{int} = -\frac{\partial w_{fld}(\lambda,\theta)}{\partial \theta}$$

$$W'_{fld} = \frac{1}{2} L(\theta) i^2$$

$$W'_{fld} = \int_V \frac{1}{2}\mu H^2 dV$$

$$\tau_{int} = \frac{\partial w'_{fld}(H,\theta)}{\partial \theta}$$

$$\tau_{int} = \frac{\partial w'_{fld}(i,\theta)}{\partial \theta}$$

Magnetic field view point

Coupled circuit view point

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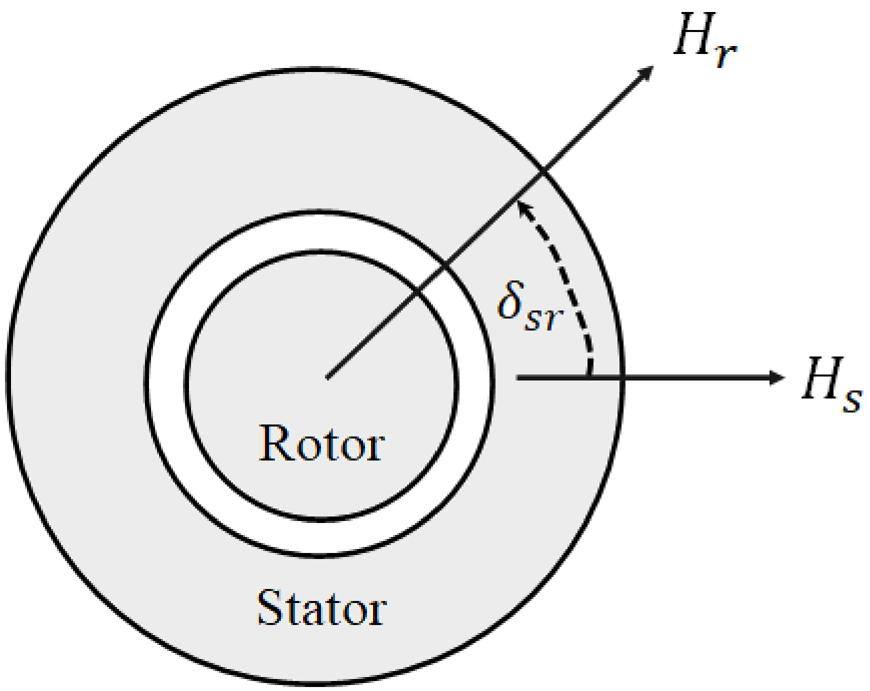
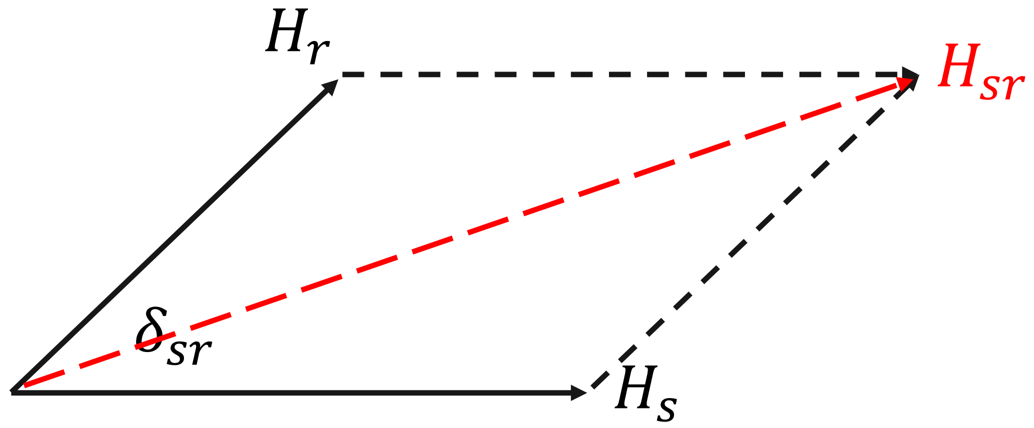
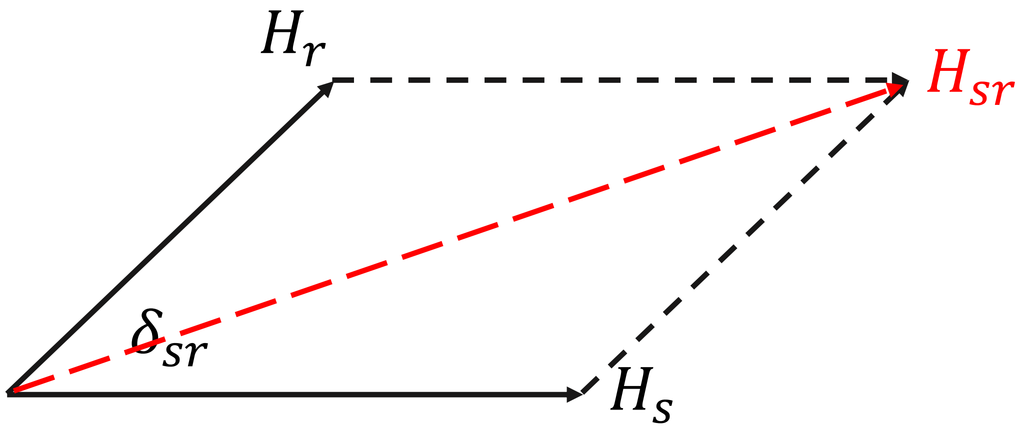
# Torque determination in electrical Machines (Magnetic field view point)



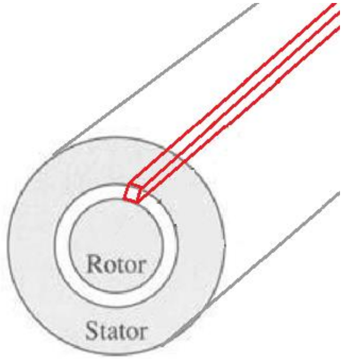



# Torque determination in electrical Machines (Magnetic field view point)




$$|H_{sr}|^2 = |H_s|^2 + |H_r|^2 + 2|H_s||H_r|cos\delta_{sr}$$

$$\omega'_{fld} = \int_v \frac{1}{2}\mu_0 \, |H_{sr}|^2 sin^2(\theta) dv$$



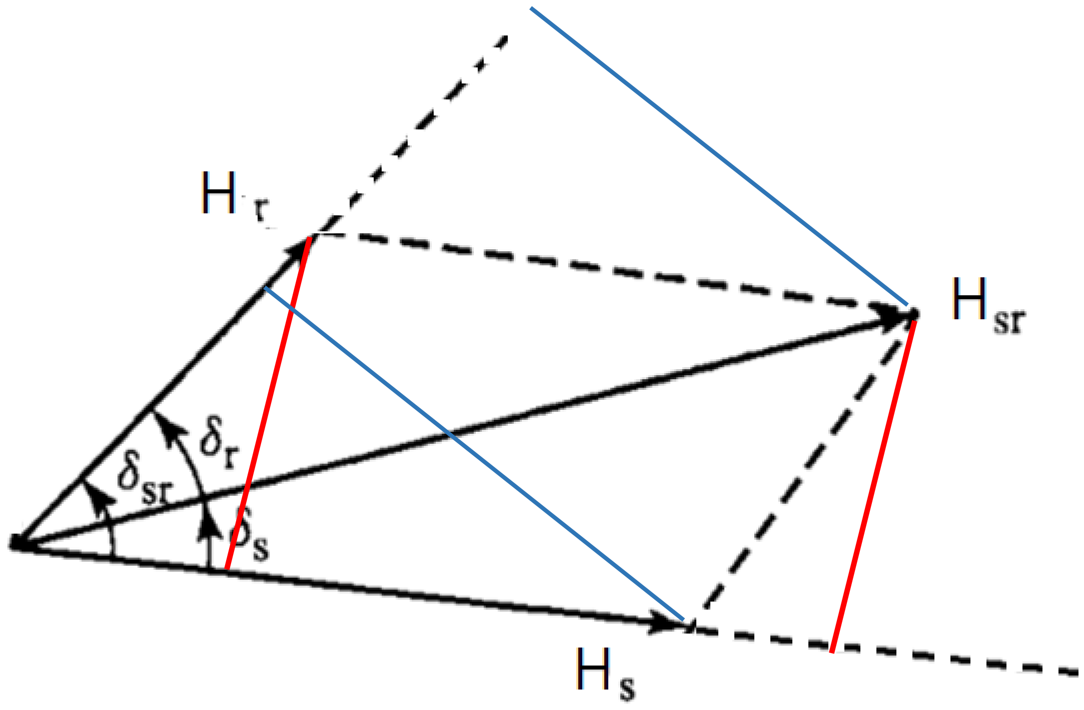

$$\omega'_{fld} = \int_0^{2\pi} \frac{1}{2}\mu_0 \, |H_{sr}|^2 sin^2(\theta) lgrd\theta = \frac{\mu_0 \pi grl}{2} |H_{sr}|^2$$

$$\omega'_{fld} = \frac{\mu_0 \pi grl}{2} |H_{sr}|^2 = \frac{\mu_0 \pi grl}{2} \{|H_s|^2 + |H_r|^2 + 2|H_s||H_r|cos\delta_{sr}\}$$

$$\tau = \frac{\partial \omega'_{fld}}{\partial \delta_{sr}}$$

$$\tau = -\mu_0 \pi grl |H_s||H_r| sin\delta_{sr}$$

# Torque determination in electrical Machines (Magnetic field view point)




$$\tau = -\mu_0 \pi g r l |H_s||H_r| sin\delta_{sr}$$

$$\tau = -\mu_0 \pi g r l |H_s||H_r| sin\delta_{sr} \qquad \tau = -\mu_0 \pi g r l |H_s||H_{sr}| sin\delta_{s} \qquad \tau = -\mu_0 \pi g r l |H_r||H_{sr}| sin\delta_{r}$$



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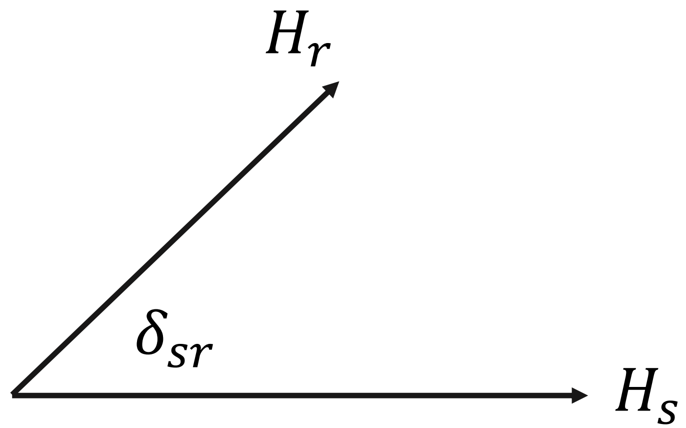
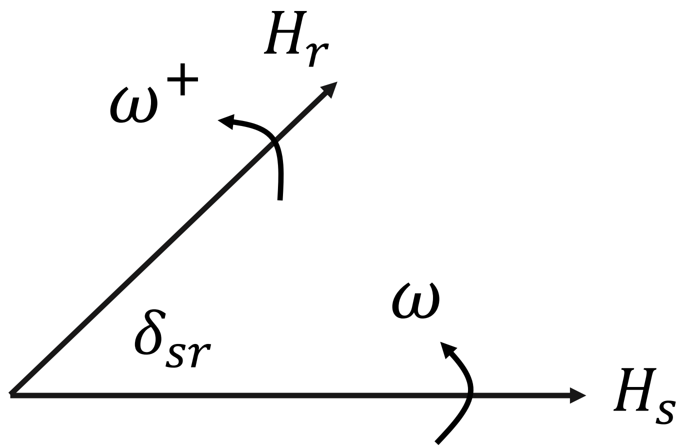
# Torque Production Condition




$$\tau = -\mu_0 \pi g r l |H_s||H_r| sin\delta_{sr}$$

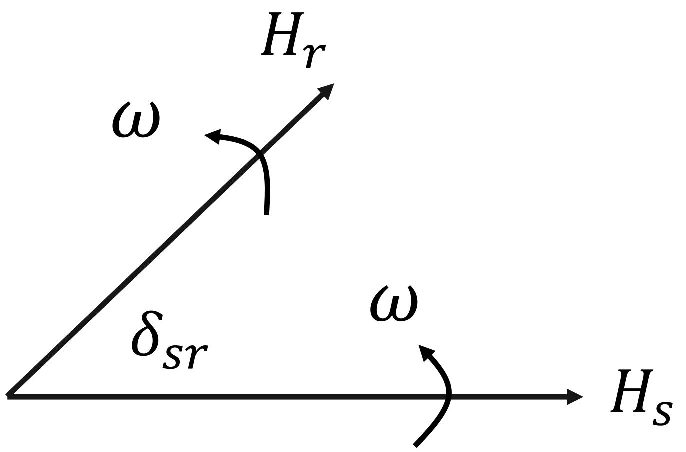
Now let's suppose that $H_s$ rotates at speed of $\omega$ and $H_r$ rotates at speed of $\omega^+$.




$$\tau = -\mu_0 \pi g r l |H_s||H_r| \sin(\ldots)$$

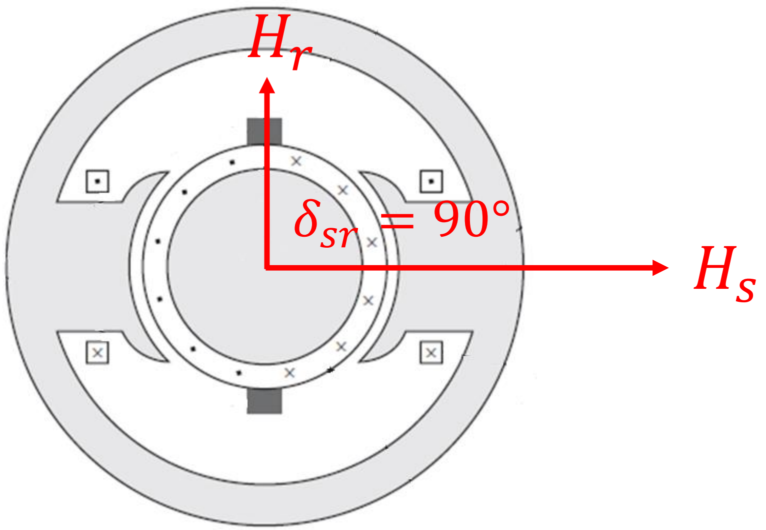
Electric machines **can produce torque at steady state** if ………………………………

# Torque Production Condition

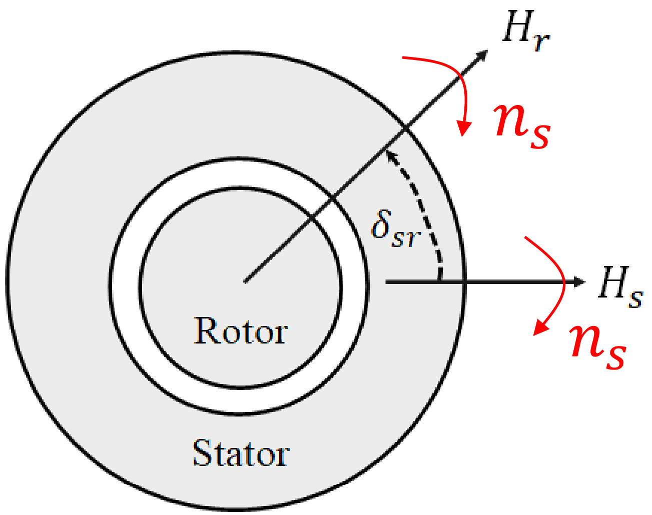



$$\tau = -\mu_0 \pi g r l |H_s||H_r| sin\delta_{sr}$$

## DC Machines:




## AC Machines ??



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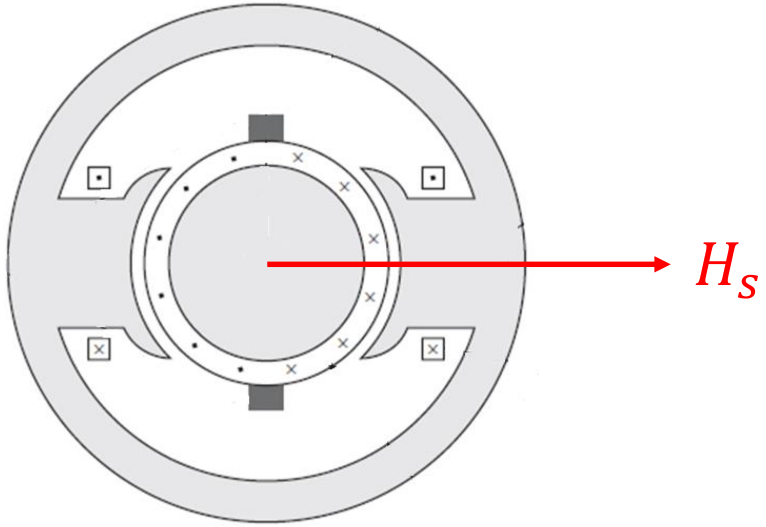
# Stator Magnetic Field in DC Machines

DC Machines:

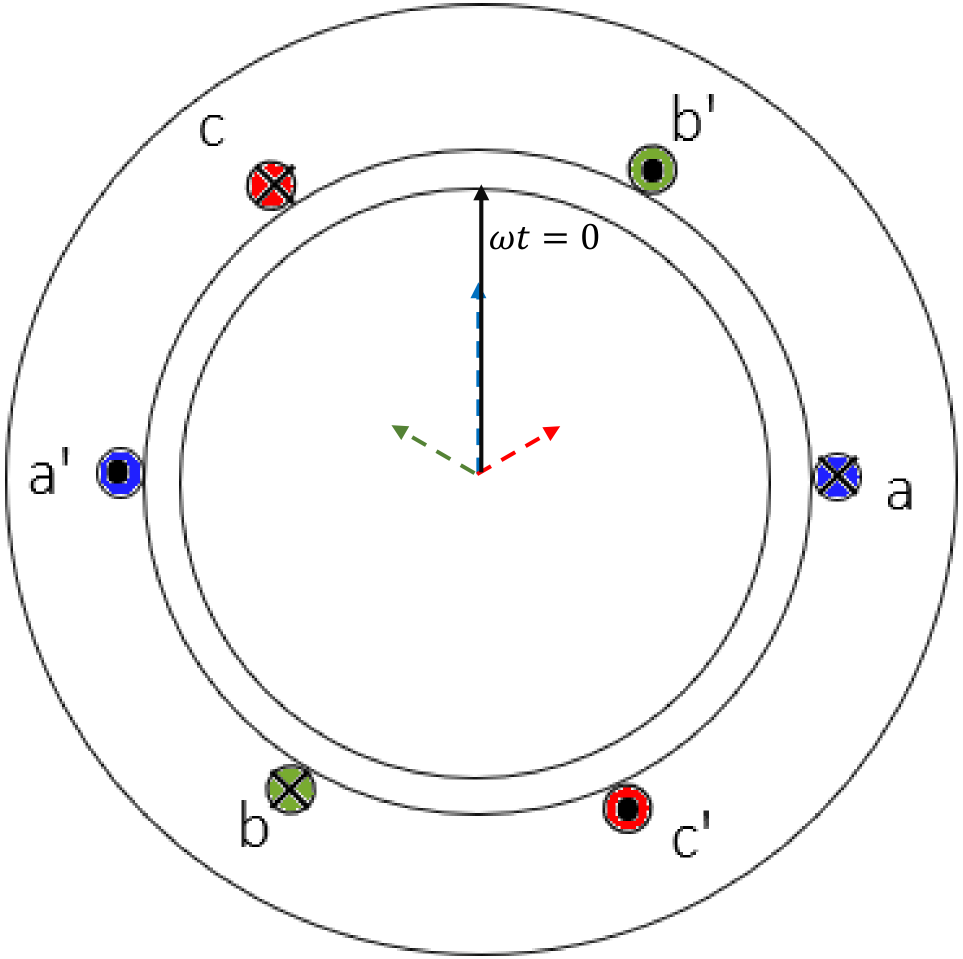


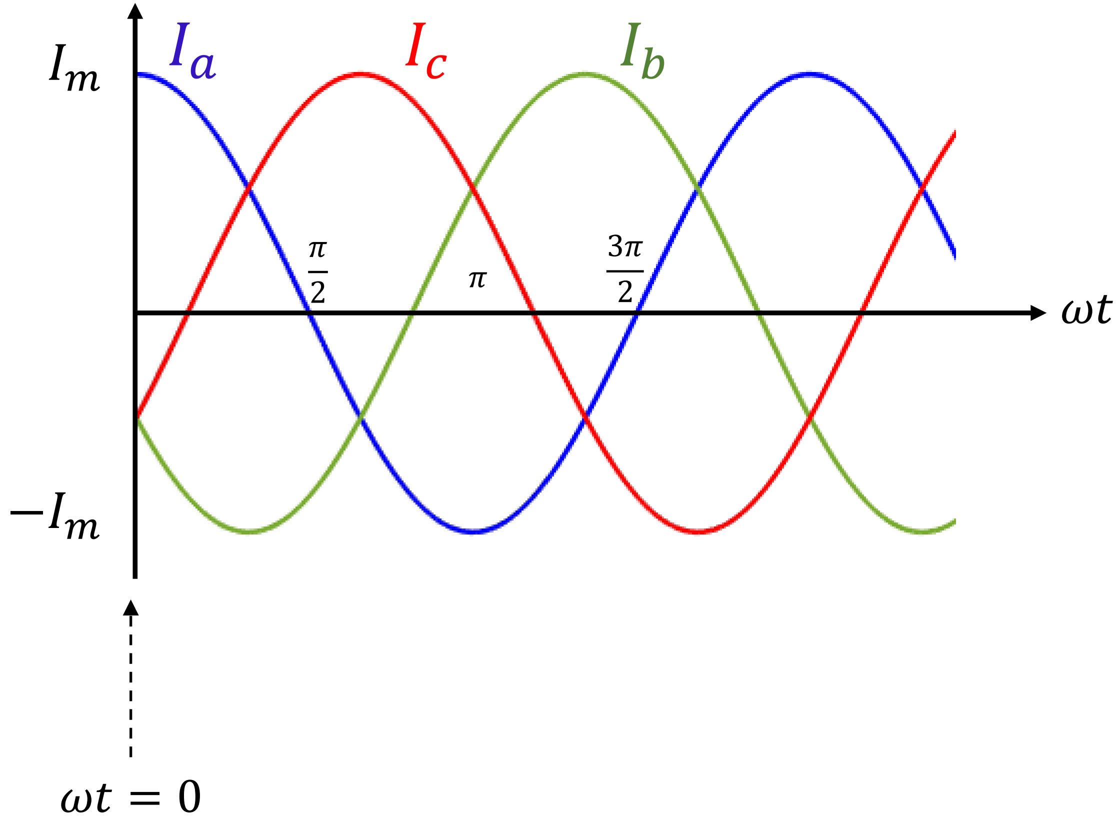

Clearly $H_s$ in DC Machines does not rotate and it is fixed.

We will show that $H_s$ in AC machines rotates.

# Stator Magnetic Field in AC Machines (Rotating MMF Waves)

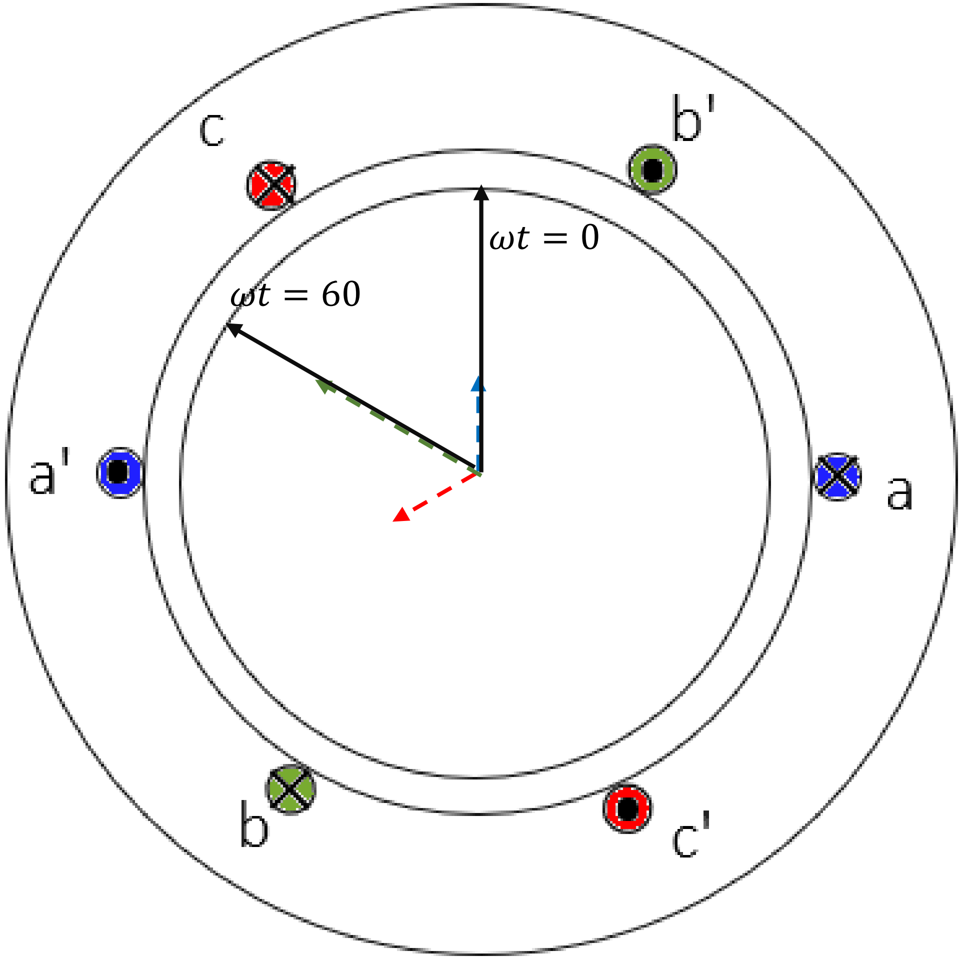
$I_a = I_m \cos(\omega t)$ $I_b = I_m \cos(\omega t + 120)$ $I_c = I_m \cos(\omega t - 120)$

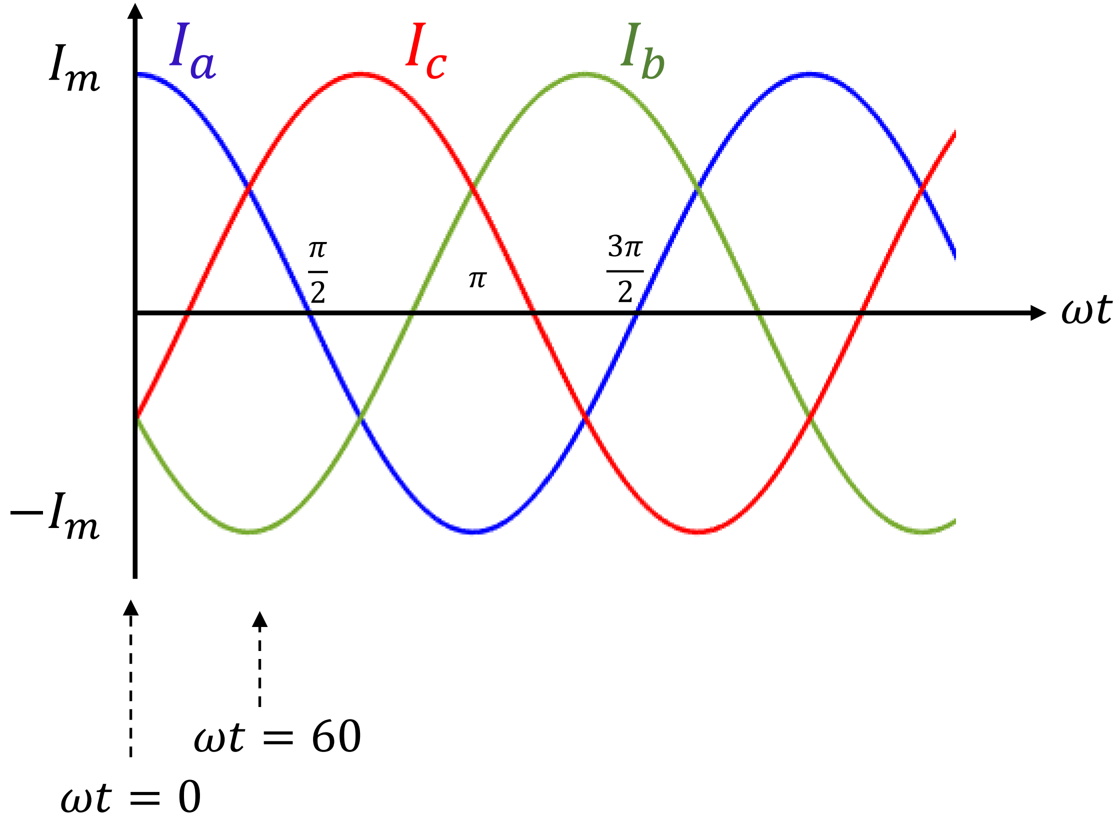


# Stator Magnetic Field in AC Machines (Rotating MMF Waves)

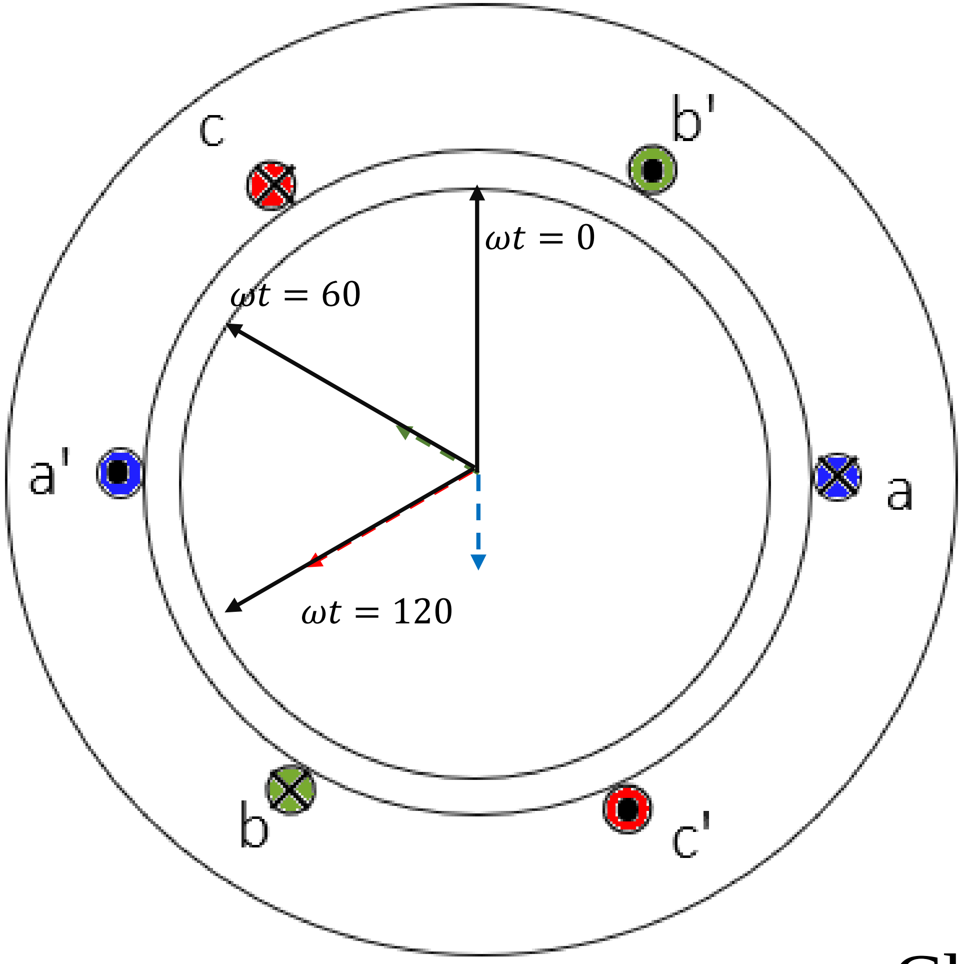
$I_a = I_m \cos(\omega t)$ $\quad I_b = I_m \cos(\omega t + 120)$ $\quad I_c = I_m \cos(\omega t - 120)$

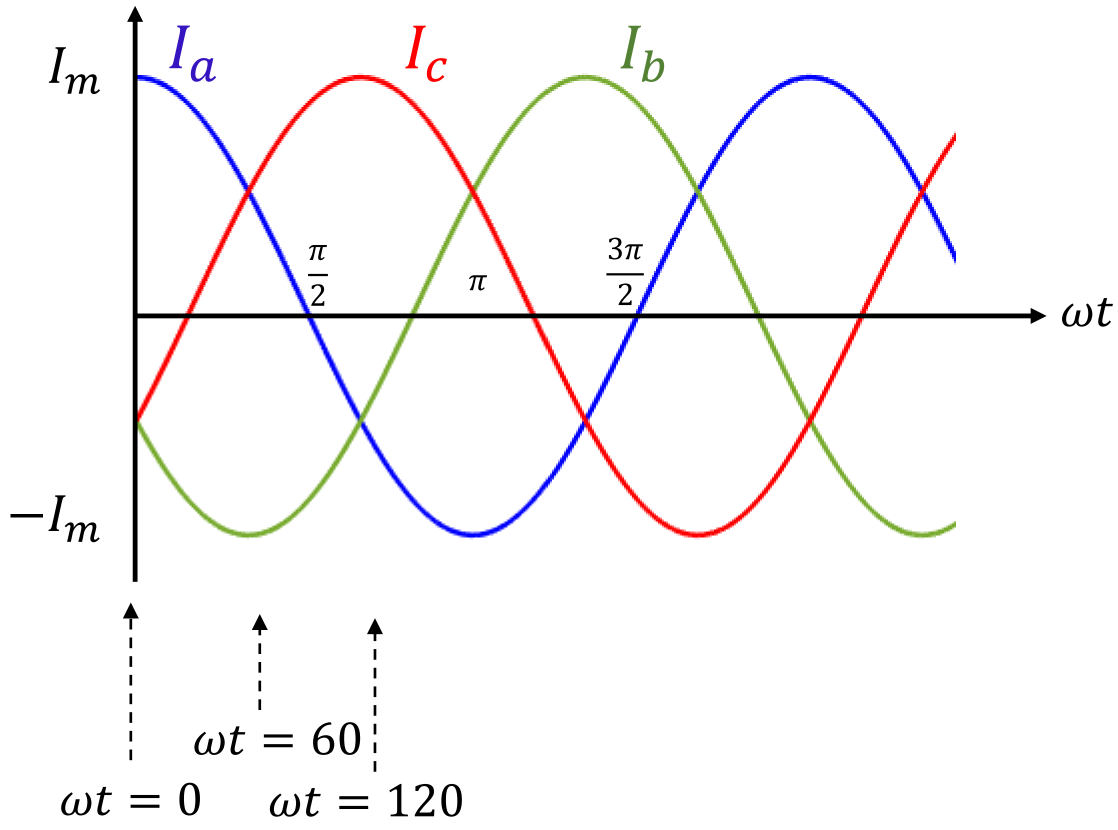


# Stator Magnetic Field in AC Machines (Rotating MMF Waves)

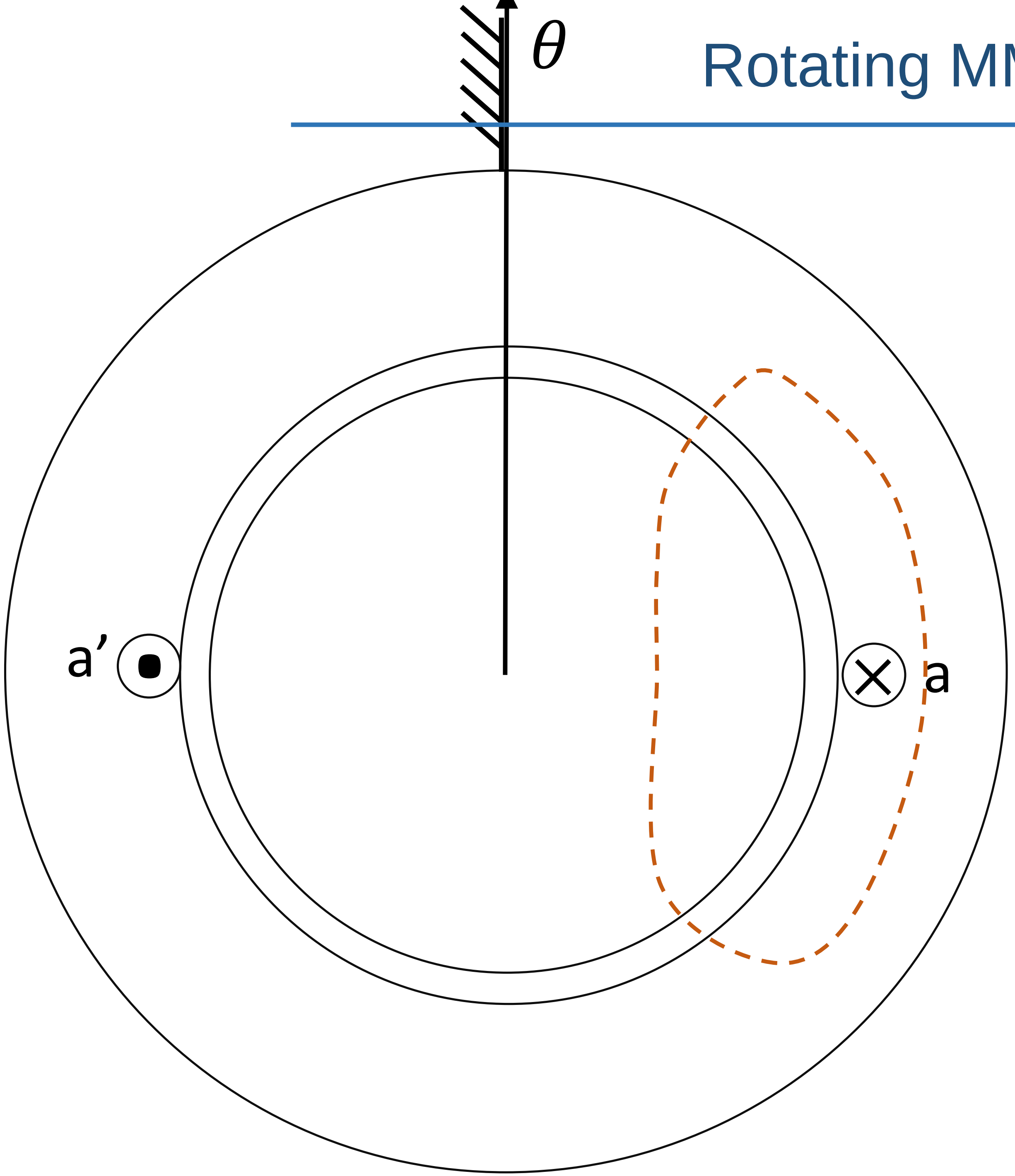
$I_a = I_m \cos(\omega t)$  $I_b = I_m \cos(\omega t + 120)$  $I_c = I_m \cos(\omega t - 120)$

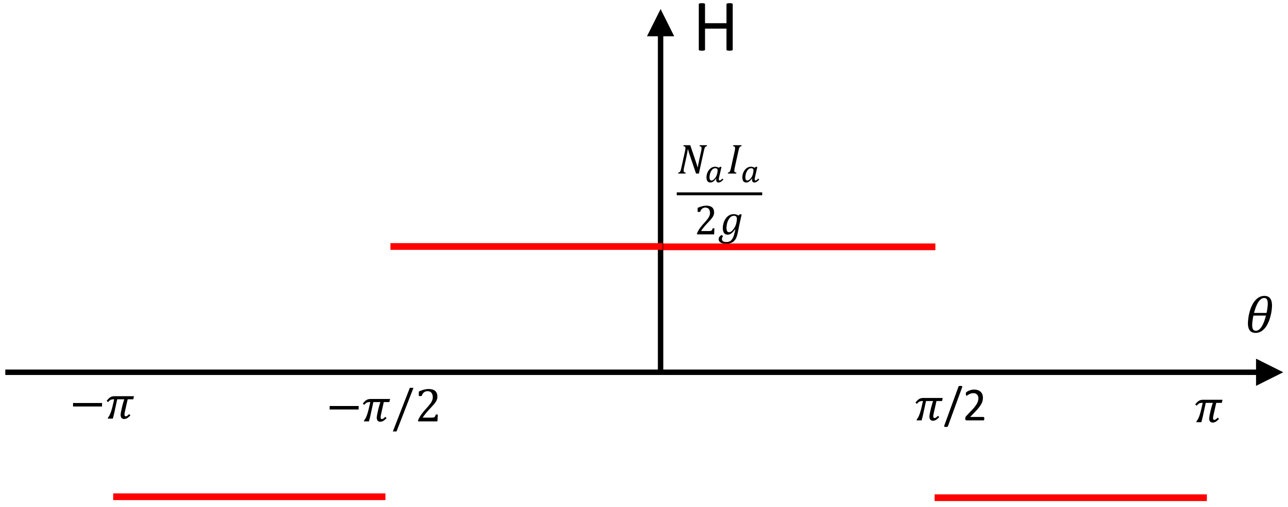


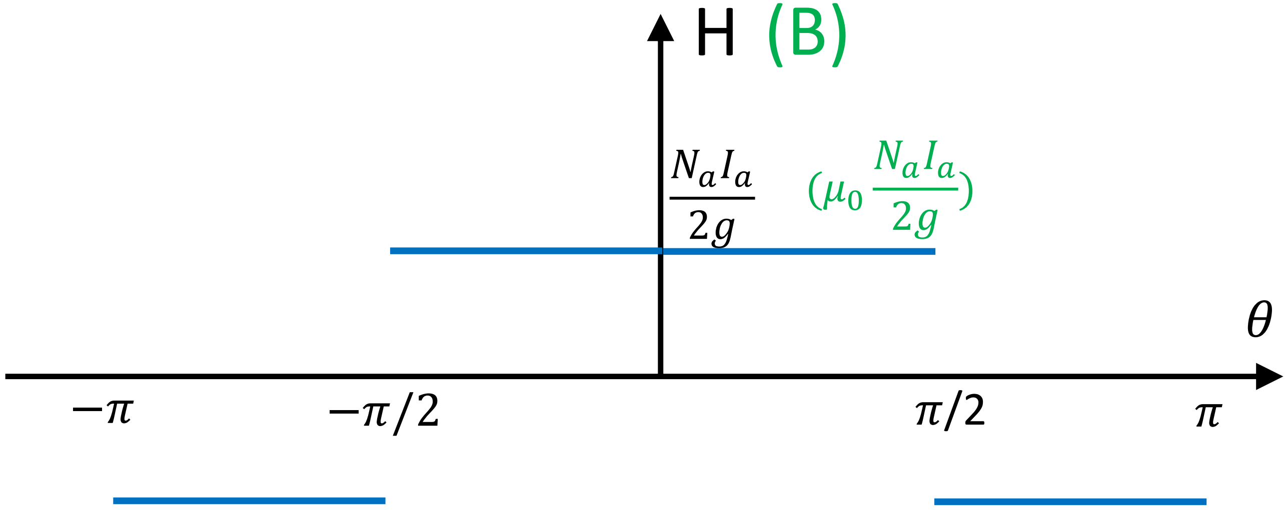




Clearly $H_s$ rotates.

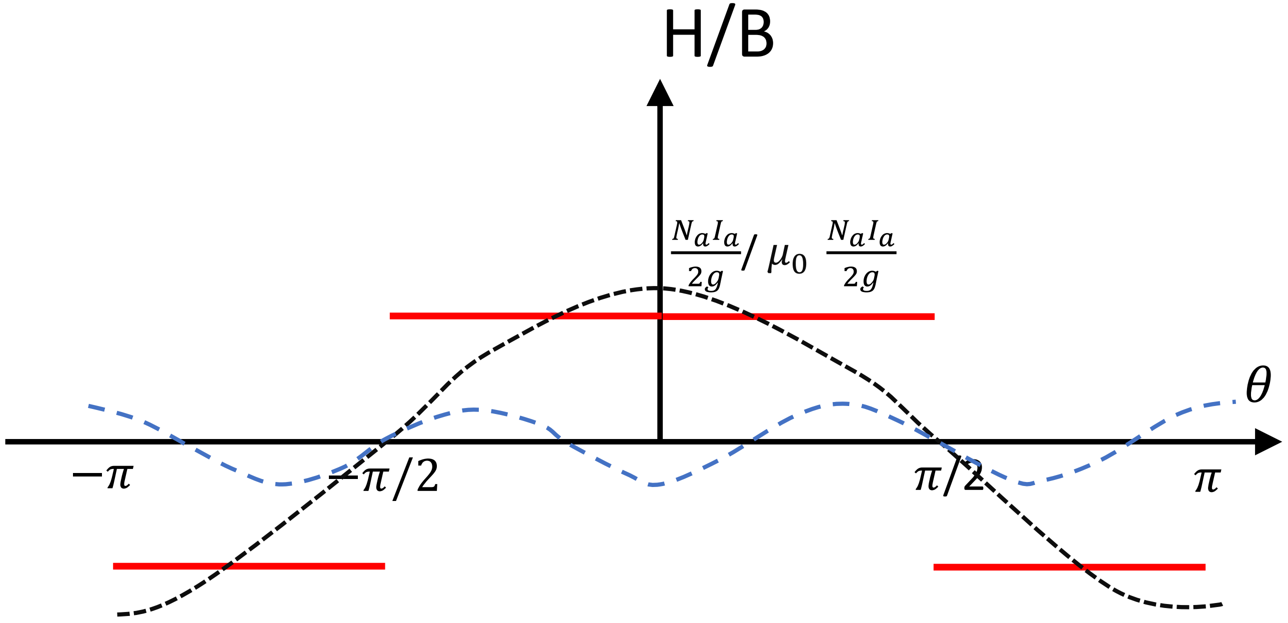
# Rotating MMF Waves in AC Machines



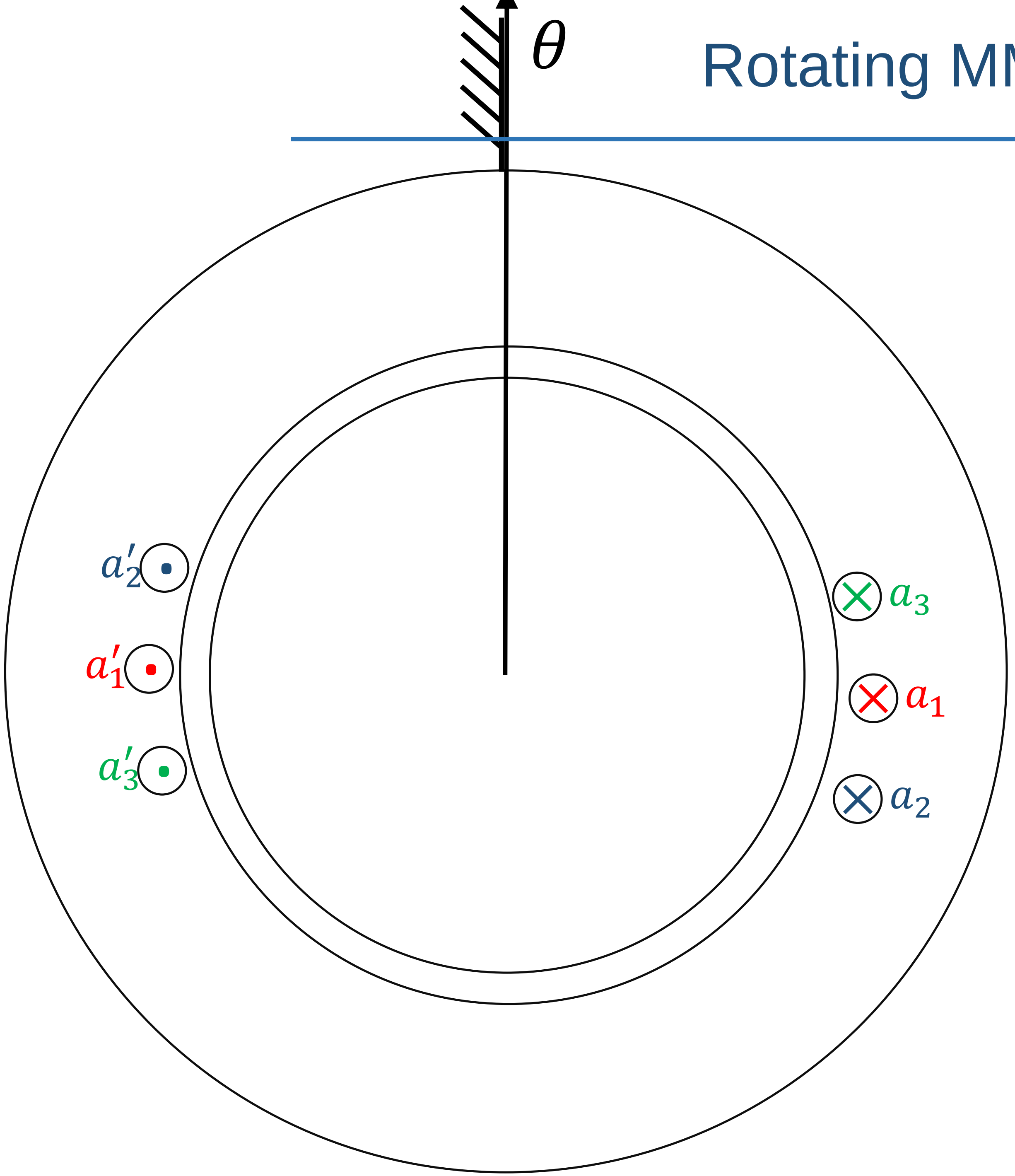



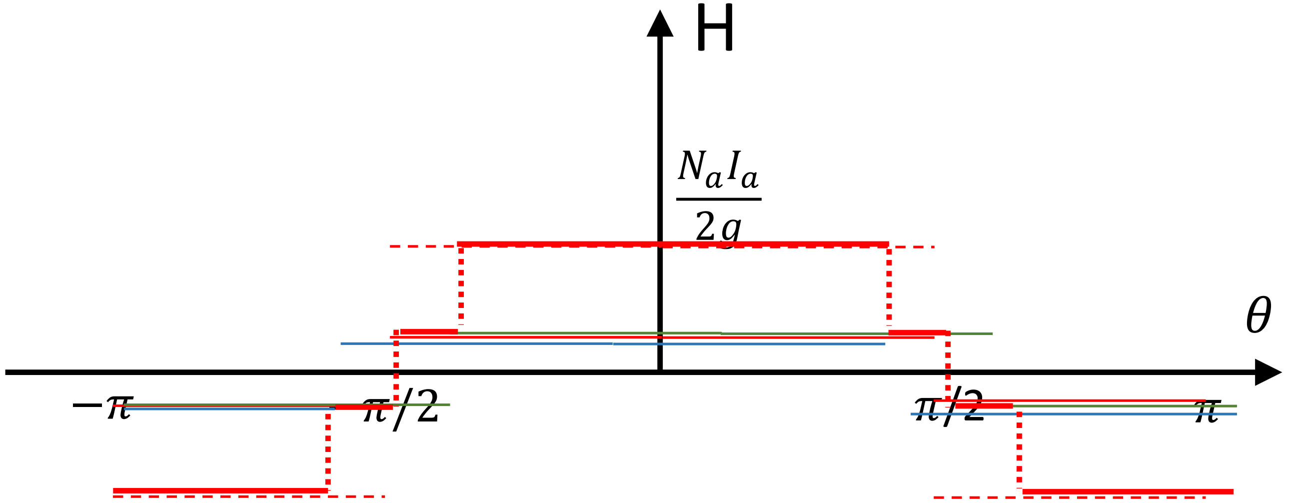
# Rotating MMF Waves in AC Machines

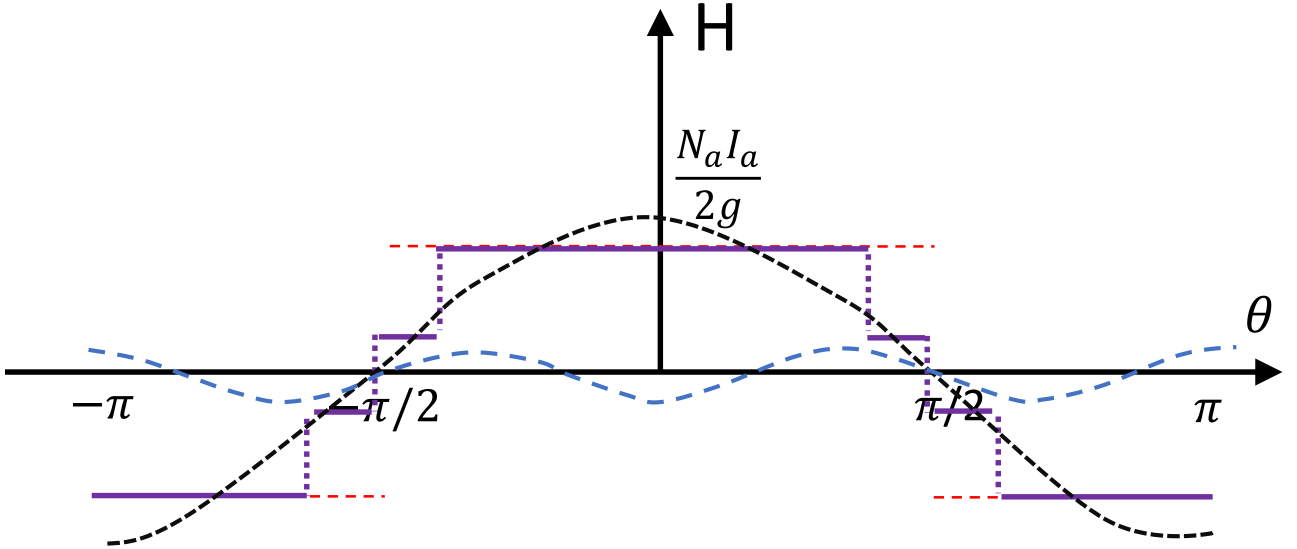



$$H = \frac{4}{\pi}\frac{N_a I_a}{2g}cos\theta - \frac{4}{3\pi}\frac{N_a I_a}{2g}cos3\theta + \frac{4}{5\pi}\frac{N_a I_a}{2g}cos5\theta - \cdots$$

# Rotating MMF Waves in AC Machines





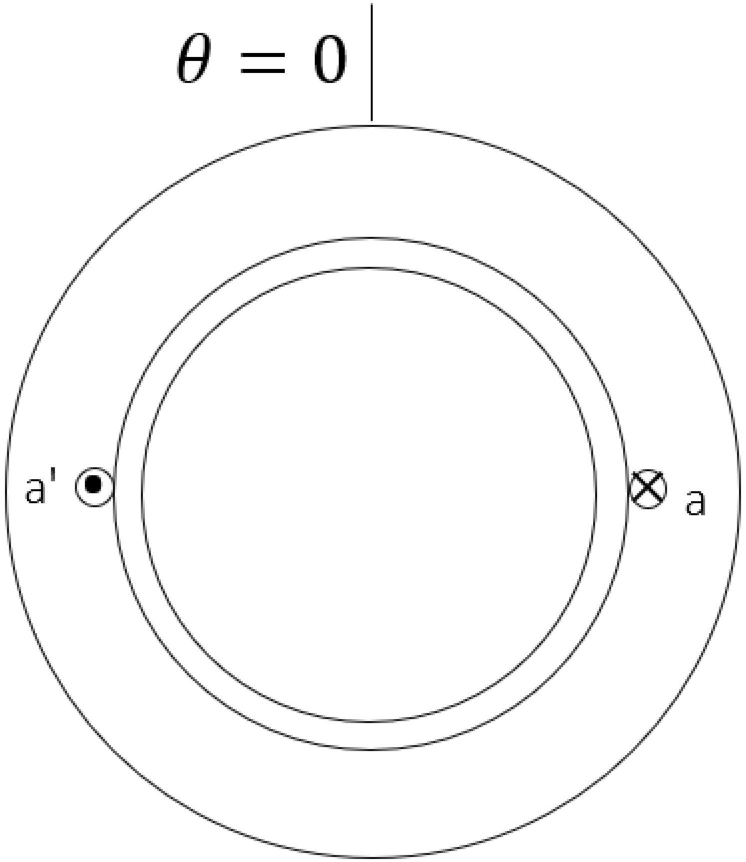
Dr. Ali Karimpour July 2024

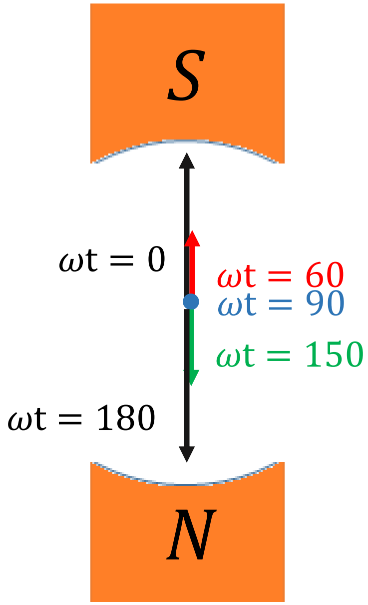
# Rotating MMF Waves in AC Machines

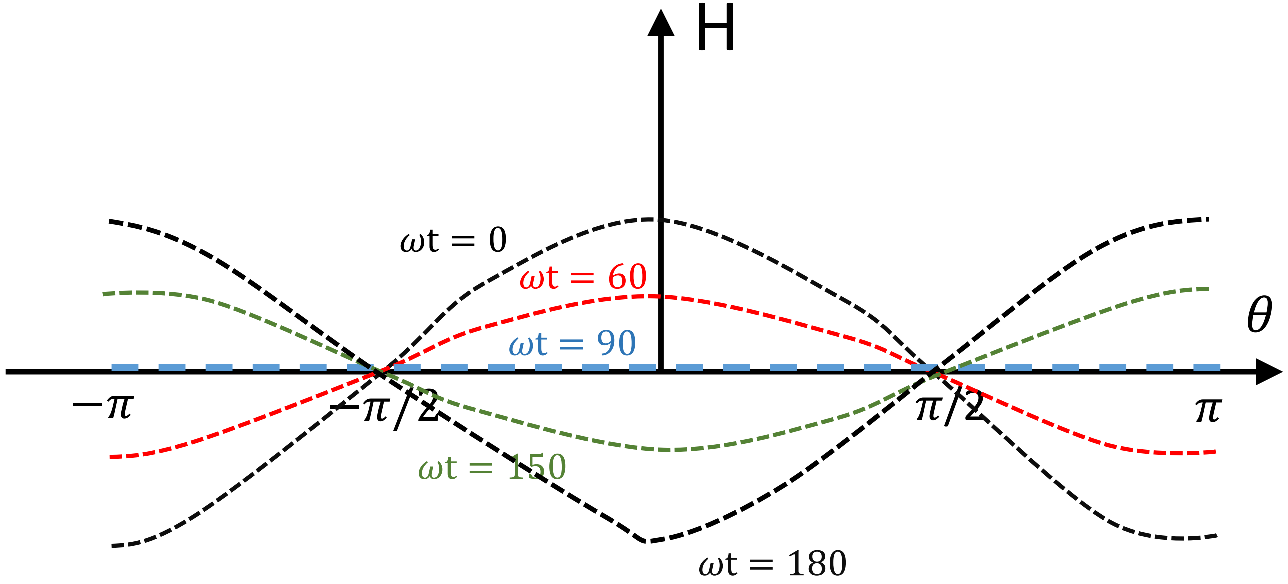
## AC machines with one phase

$$I_a = I_m \cos(\omega t)$$

$$\overrightarrow{H_a} = \frac{4}{\pi}\frac{k_w N_a I_a}{2g} cos\theta \qquad \overrightarrow{H_a} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \cos(\omega t)\cos(\theta)$$



# Rotating MMF Waves in AC Machines

## AC machines with one phase

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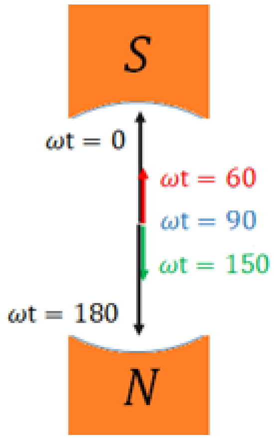
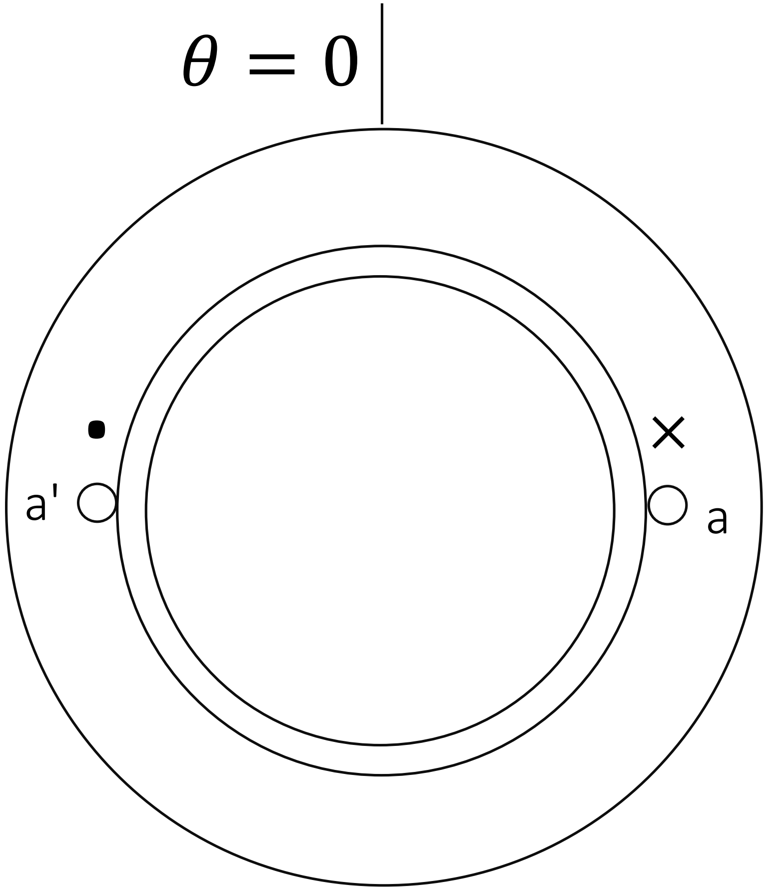
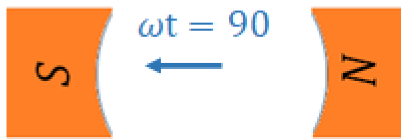
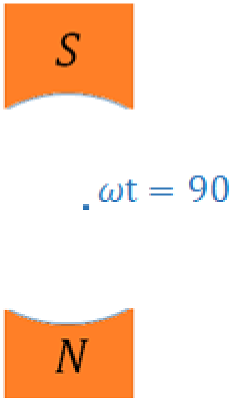
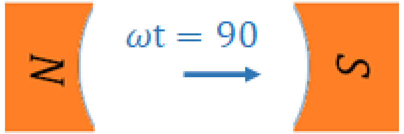



$$\overrightarrow{H_a} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta - \omega t) + \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta + \omega t)$$

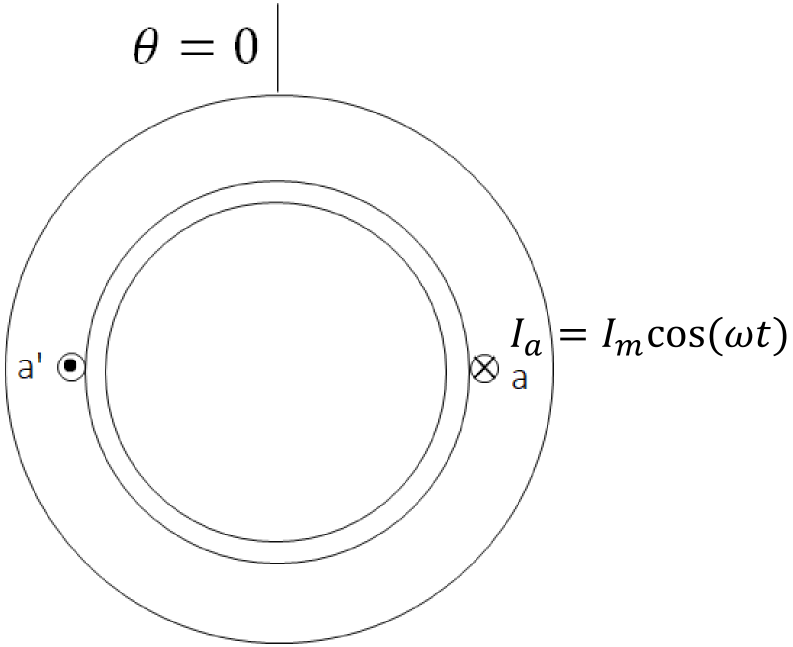


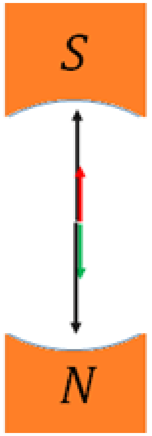



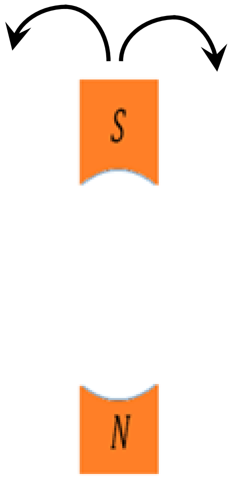



# Rotating MMF Waves in AC Machines

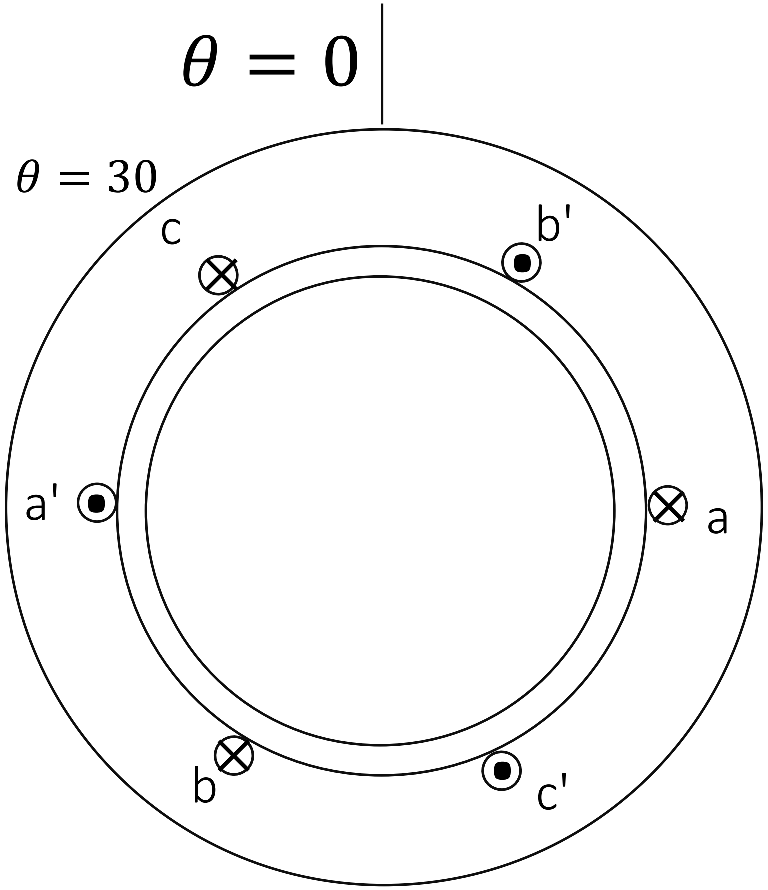
## AC machines with one phase



# Rotating MMF Waves in AC Machines




$$H_a = \frac{4}{\pi}\frac{k_w N_a I_a}{2g} cos\theta \qquad I_a = I_m \cos(\omega t)$$

$$\overrightarrow{H_a} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta - \omega t) + \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta + \omega t)$$

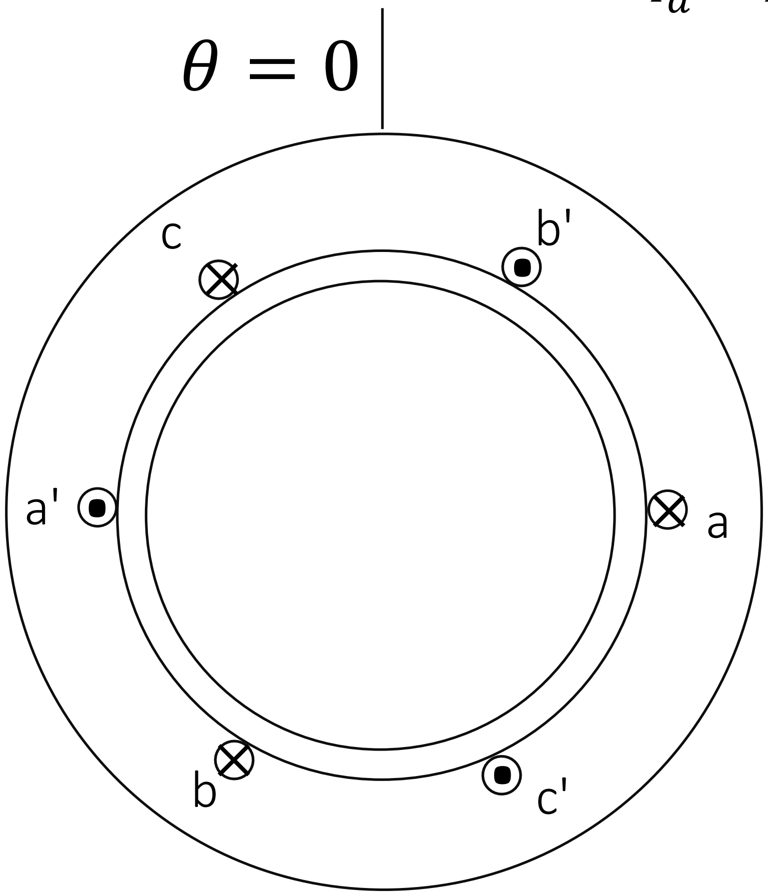
$$\overrightarrow{H_b} = \frac{4}{\pi}\frac{k_w N_a I_b}{2g}\cos(\theta + 120) \qquad I_b = I_m \cos(\omega t + 120)$$

$$\overrightarrow{H_b} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta - \omega t) + \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta + \omega t + 240)$$

$$\overrightarrow{H_c} = \frac{4}{\pi}\frac{k_w N_a I_c}{2g}\cos(\theta - 120) \qquad I_c = I_m \cos(\omega t - 120)$$

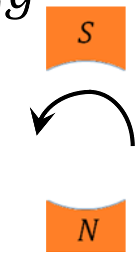
$$\overrightarrow{H_c} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta - \omega t) + \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta + \omega t - 240)$$

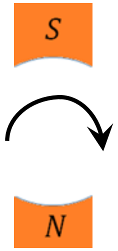
# Rotating MMF Waves in AC Machines



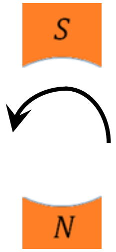

$$I_a = I_m \cos(\omega t) \qquad I_b = I_m \cos(\omega t + 120) \qquad I_c = I_m \cos(\omega t - 120)$$

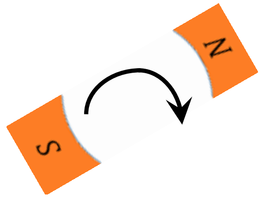
$$\overrightarrow{H_a} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta - \omega t) + \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta + \omega t)$$



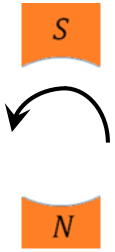



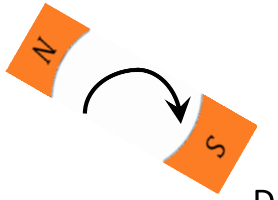

$$\overrightarrow{H_b} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta - \omega t) + \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta + \omega t + 240)$$



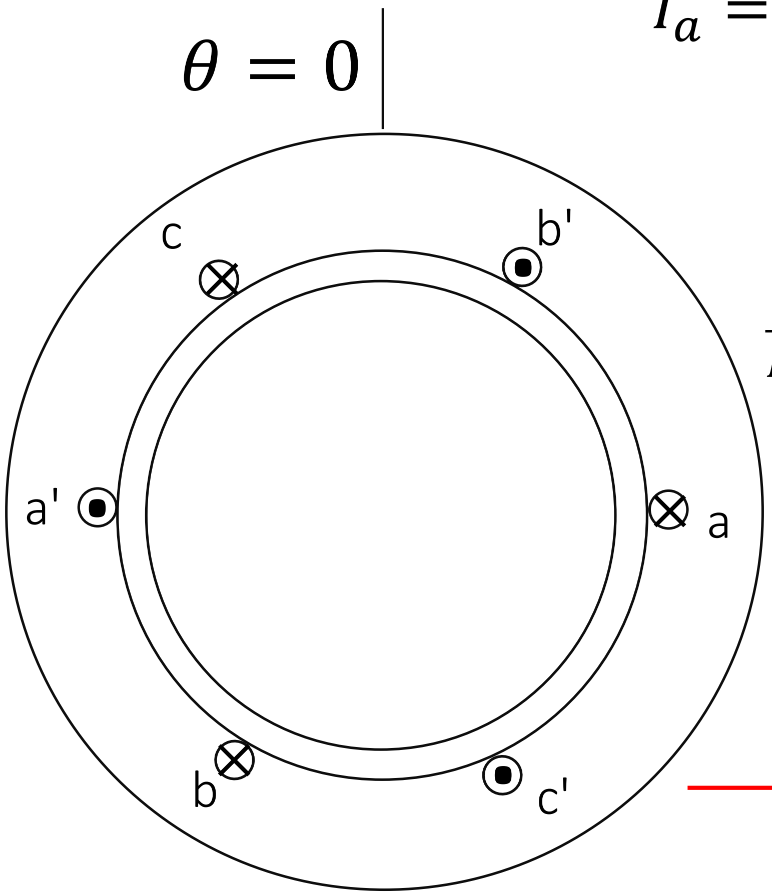




$$\overrightarrow{H_c} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta - \omega t) + \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta + \omega t - 240)$$



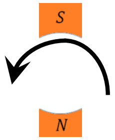



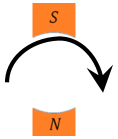
# Rotating MMF Waves in AC Machines



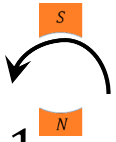

$$I_a = I_m\cos(\omega t) \qquad I_b = I_m\cos(\omega t + 120) \qquad I_c = I_m\cos(\omega t - 120)$$

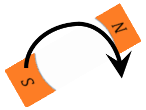
$$\overrightarrow{H_a} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta - \omega t) + \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta + \omega t)$$



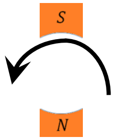



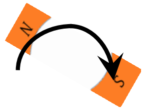

$$\overrightarrow{H_b} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta - \omega t) + \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta + \omega t + 240)$$



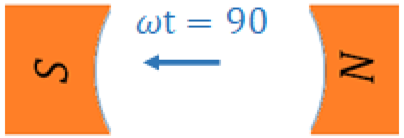




$$\overrightarrow{H_c} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta - \omega t) + \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{1}{2}\cos(\theta + \omega t - 240)$$

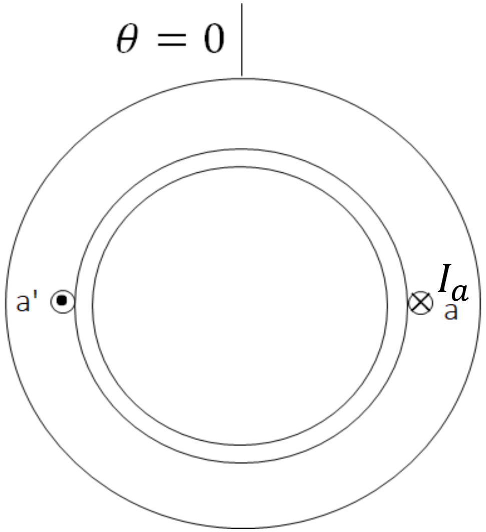


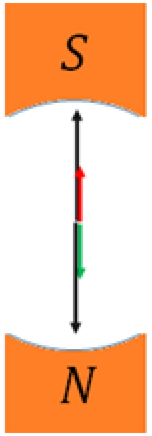

$$\overrightarrow{H_s} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{3}{2}\cos(\theta - \omega t)$$

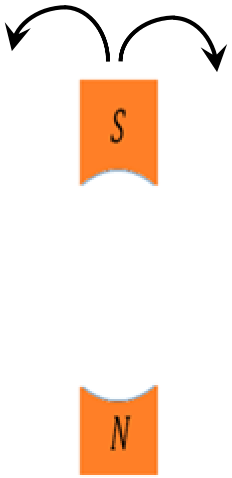


# Rotating field in AC machines

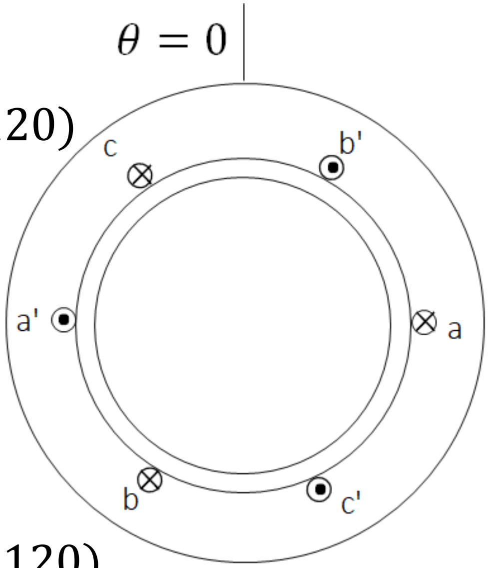



$I_a = I_m \cos(\omega t)$



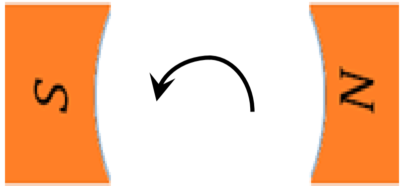




$I_c = I_m \cos(\omega t - 120)$

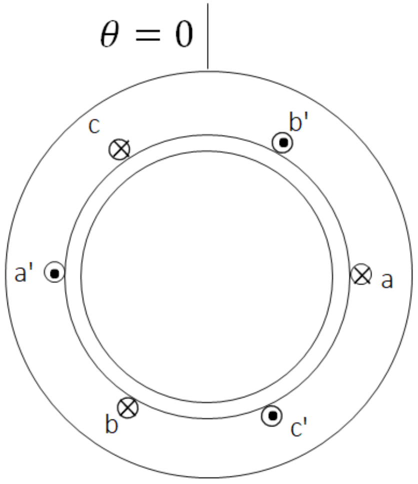



$I_a = I_m \cos(\omega t)$

$I_b = I_m \cos(\omega t + 120)$



# Torque determination in cylindrical AC Machine (Electromagnetic view point)




$$I_a = I_m \cos(\omega t)$$

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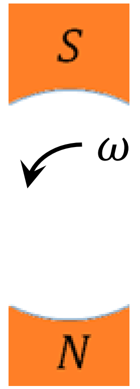
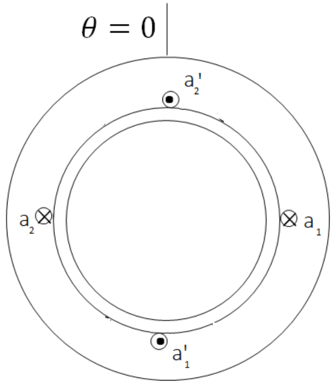
$$\overrightarrow{H_s} = \frac{4}{\pi}\frac{k_w N_a}{2g} I_m \frac{3}{2}\cos(\theta - \omega t)$$

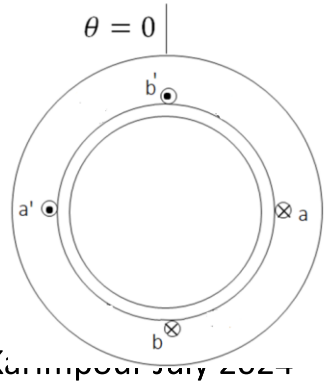



Exercise 2: What does happen if we change two currents?

Exercise 3: What does happen if we have a three-phase four poles machine?



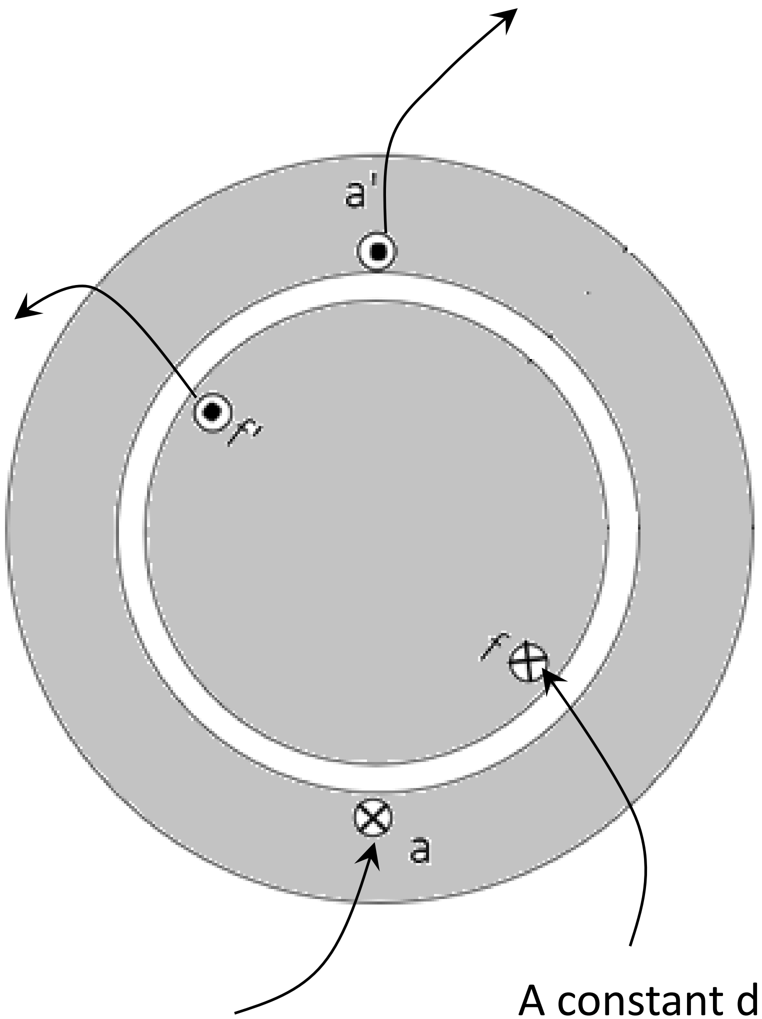

Exercise 4: What does happen if we have a two-phase two poles machine?




Exercise 5: What does happen if we apply a capacitance in phase b and then use same voltage for both phase.

# Torque Production Condition



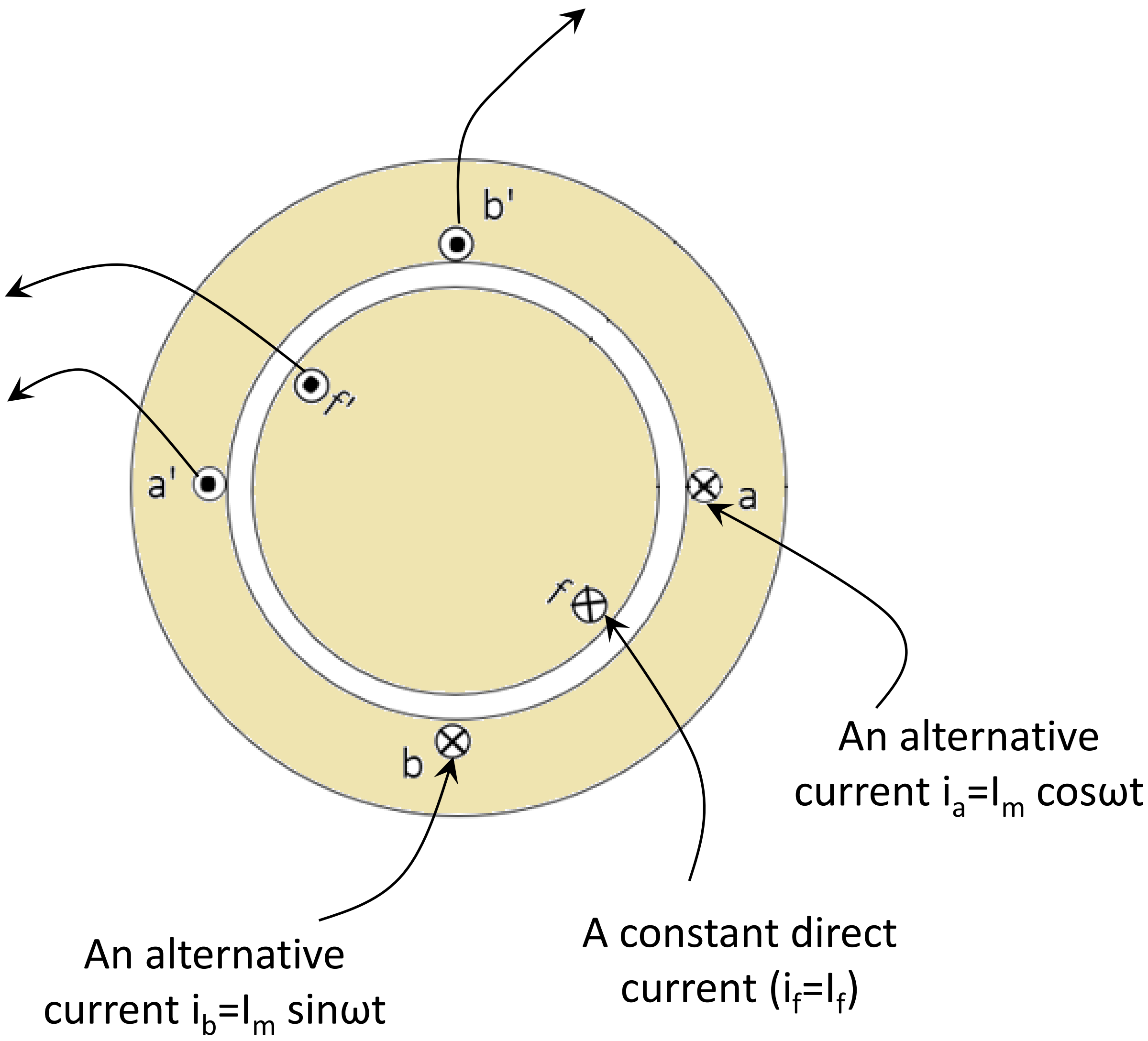



A constant direct current ($i_f$=$I_f$)

An alternative current $i_a$=$I_m$ sinωt

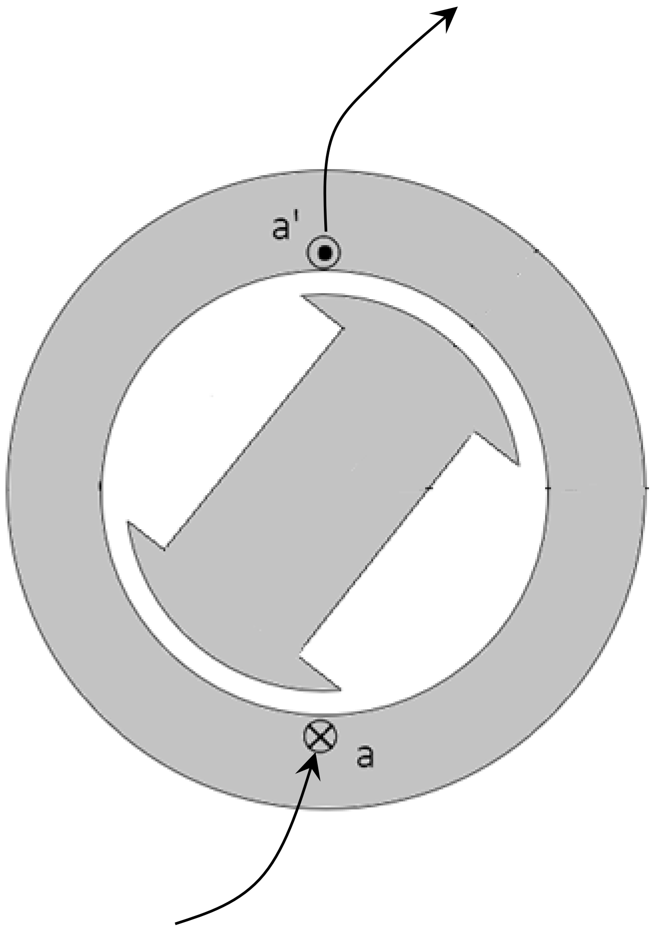
The motor can just work at the speed of …... in ….. or …...

# Torque Production Condition




The motor can just work at the speed of …... in …..

# Torque Production Condition




An alternative current $i_a = I_m \sin\omega t$

The motor can just work at the speed of …... in ….. or …...

# Torque Production Condition



**Exercise 6: (Final Exam, 2022):** In the following figure, θ is the angle between the stator winding axis and the rotor axis. Winding a has a constant current of 20.

Note: To solve this problem, rely on physical understanding; mathematical relations are not required.

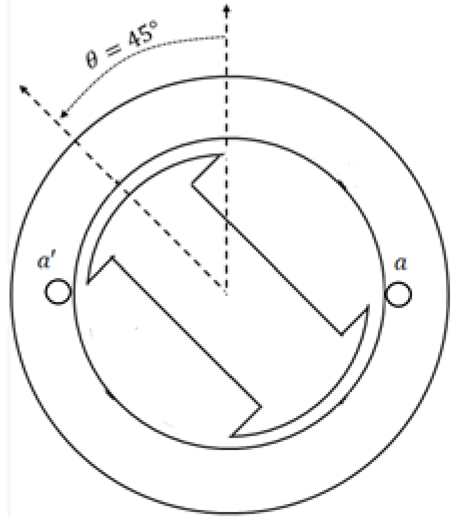
Determine the direction of the torque in terms of clockwise (cw) or counterclockwise (ccw).

**a:** For θ = 90°, determine the presence and direction of the torque.

**b:** For θ = 0°, determine the presence and direction of the torque.

**c:** For θ = 45°, determine the presence and direction of the torque.

**d:** For θ = −45°, determine the presence and direction of the torque.




**Exercise 7: (Final Exam, 2022):** Consider the following figure. Assume that the positive current enters from the cross-marked side and exits from the other side. Given the following currents, comment on the speed and direction of the rotating magnetic field of the stator.

(Note: The specific currents to be considered should be provided for a complete analysis.)

$$i_a = 5\sin(100\pi t + 33)\,, i_b = 5\sin(100\pi t + 123)$$