Overview Electrical Machines and Drives

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- 11-9 1.2-3: Magnetic circuits, Principles
- 14-9 3-4.2: Principles, DC machines
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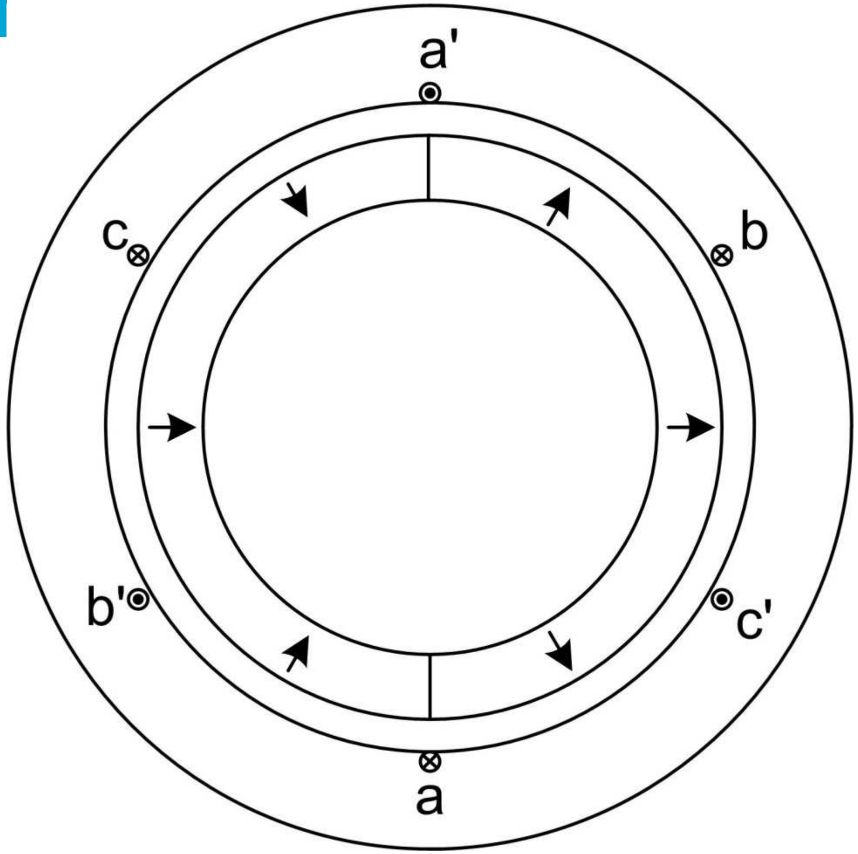
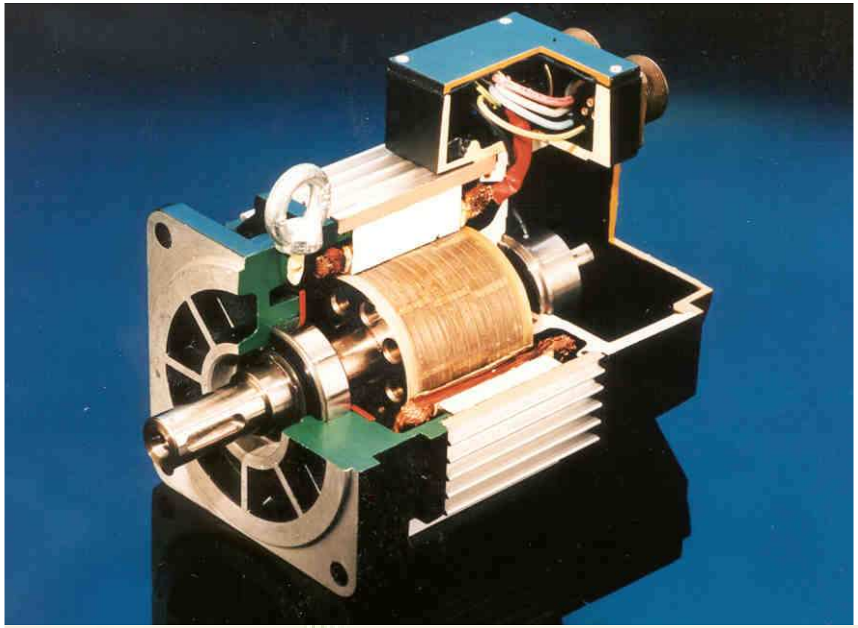
- 19-10: rest, questions
- 9-11: exam

Permanent magnet AC machines (6.13)

- Introduction
- Calculation example
- Brushless DC motor (rectangular / trapezoidal waveforms)
- PMSM (sinusoidal waveforms)
- For these machine types
  - Construction
  - Electromotive force
  - Voltage equations and equivalent circuit
  - Power balance
  - Force or torque

PM AC machine





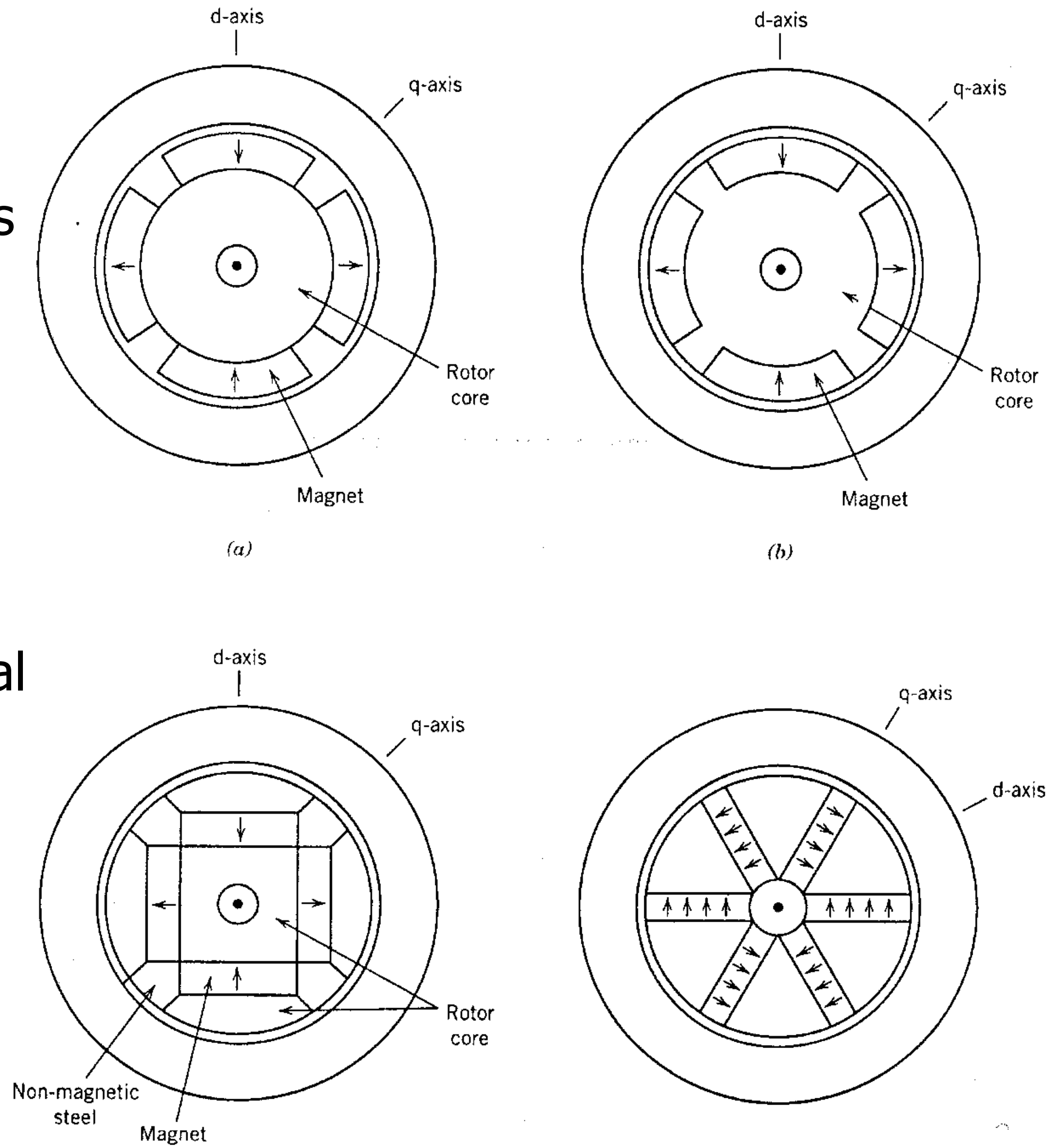
Rotor layouts

1 surface mounted magnets
- *Ld≈Lq*
- *L* small because of large air gap

2 inset magnets
- *Ld<Lq*
- reluctance torque

3 embedded magnets, radial magnetization
- *Ld<Lq*
- reluctance torque

4 embedded magnets, circumferential magnetization
- flux concentration



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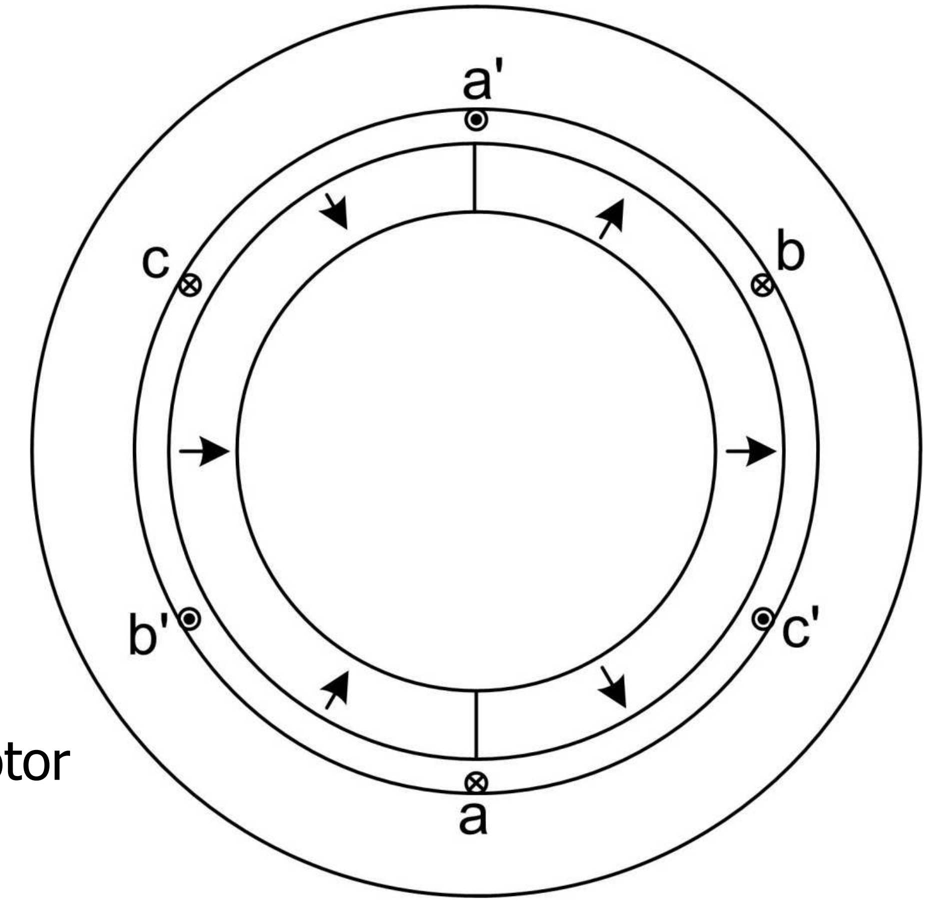
PM AC machine: calculation example

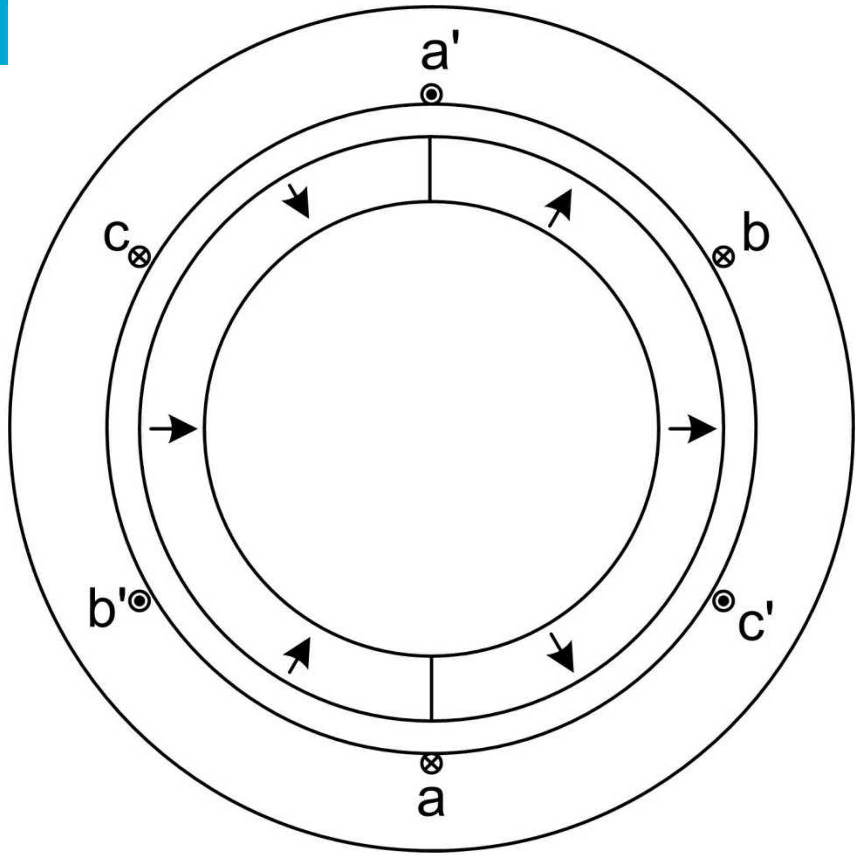
- air gap radius r_s
- axial length l_s
- magnet length l_m
- air gap length l_g
- number of turns N_s
- remanent flux density B_{rm}
- recoil permeability μ_{rm}
- rotor speed ω_m

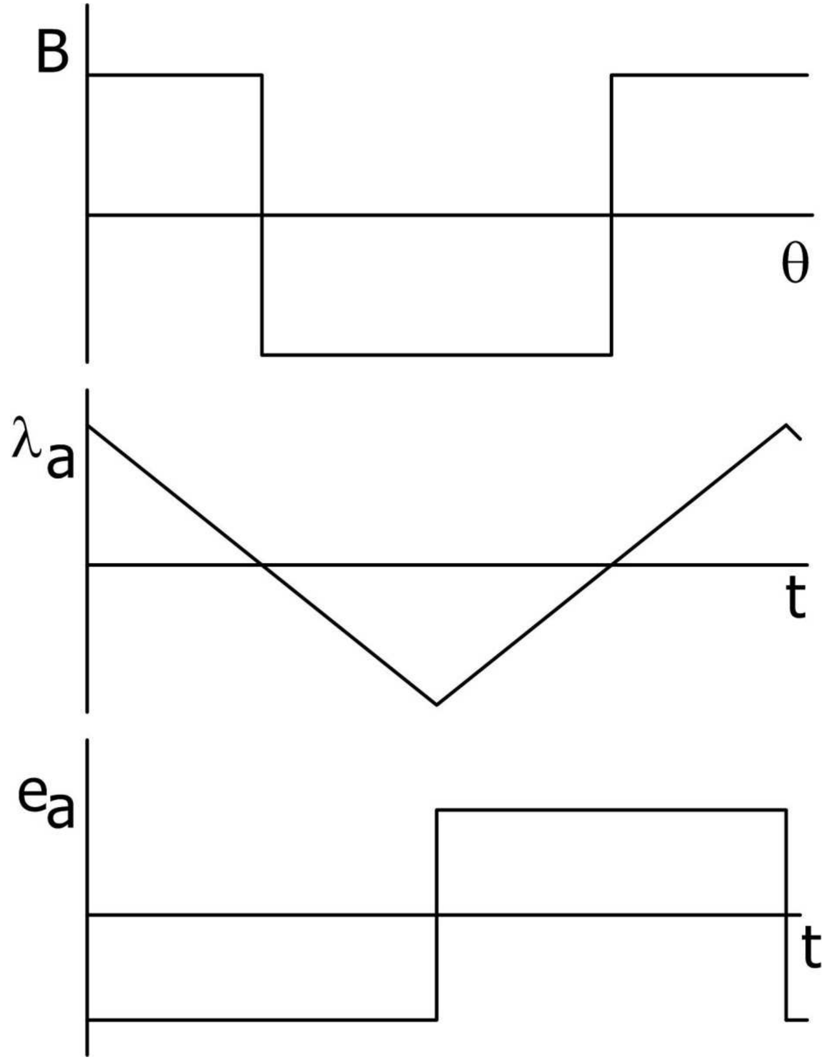
Determine and sketch

- air gap flux density in gap
- flux linkage as a function of rotor position
- induced voltage



PM AC machine





PM AC machine

Using Ampère's law:

$$\oint_{C_m} \vec{H} \cdot \vec{\tau}\, \mathrm{d}s = \iint_{S_m} \vec{J} \cdot \vec{n}\, \mathrm{d}A \qquad 2H_m l_m + 2H_g l_g = 0$$

Magnetic flux continuity

$$\oiint_{S} \vec{B} \cdot \vec{n}\, \mathrm{d}A = 0 \qquad B_m = B_g$$

BH curve of magnet $B_m = \mu_0 \mu_{rm} H_m + B_r$

BH curve of air $B_g = \mu_0 H_g$

Result

$$B_g = \frac{l_m}{l_m + \mu_{rm} l_g} B_r$$

PM AC machine

For one phase without load:

$$\lambda_{\max} = NBA = N_s B_g \pi r_s l_s$$

$$E_{pm\max} = \frac{\mathrm{d}\lambda}{\mathrm{d}t} = 4f\lambda_{pm\max} = 2N_s B_g r_s l_s \omega_m$$

$$E_{pm\max} = Blv$$

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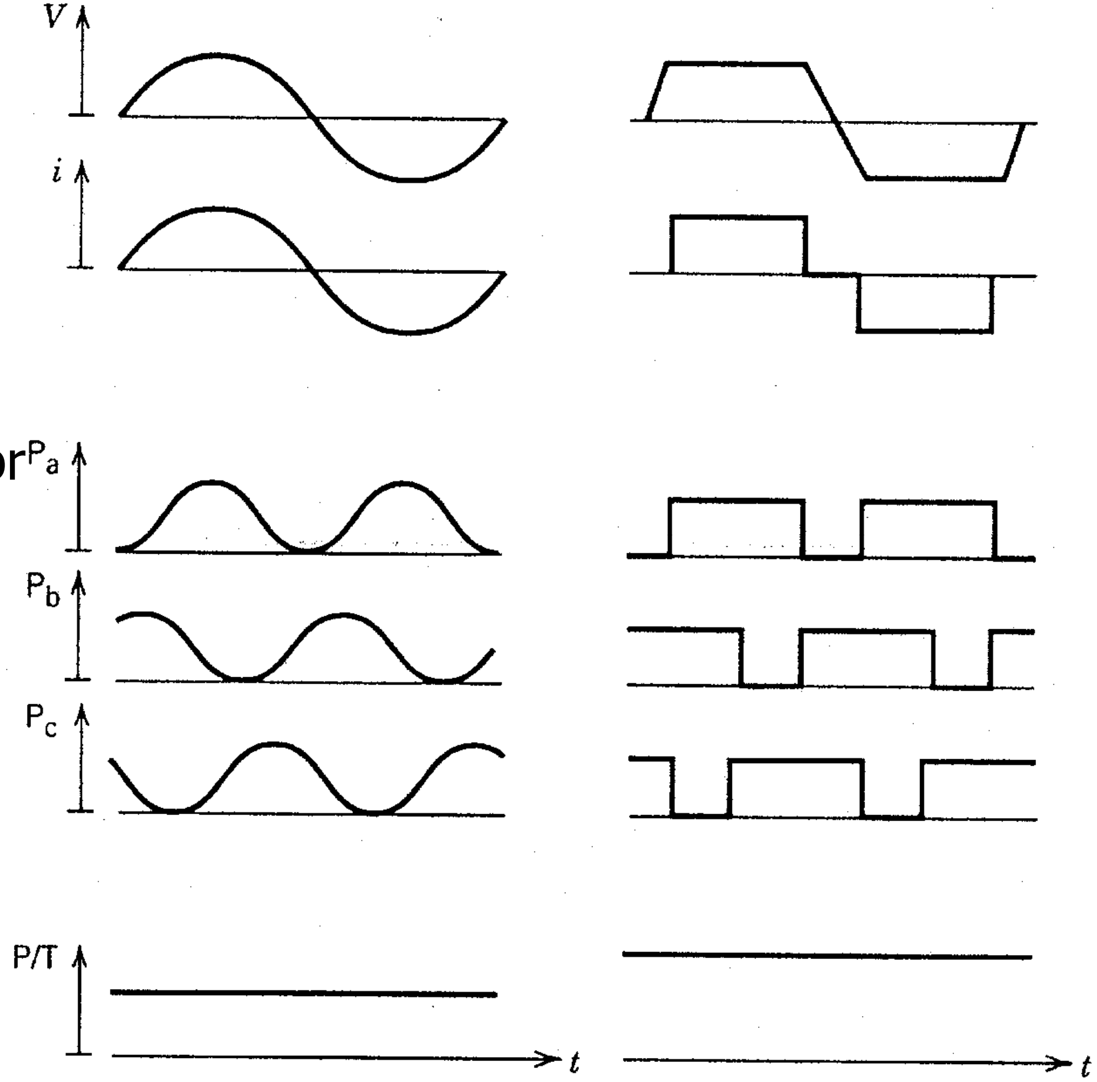
Construction: PMAC or BDCM

PMSM:

- sinusoidal B
- distributed windings
- sinusoidal voltage
- sinusoidal currents
- continuous position sensor
- smooth force

BDCM:

- rectangular B
- concentrated windings
- trapezoidal voltage
- rectangular currents
- 6 step position sensor
- force ripple

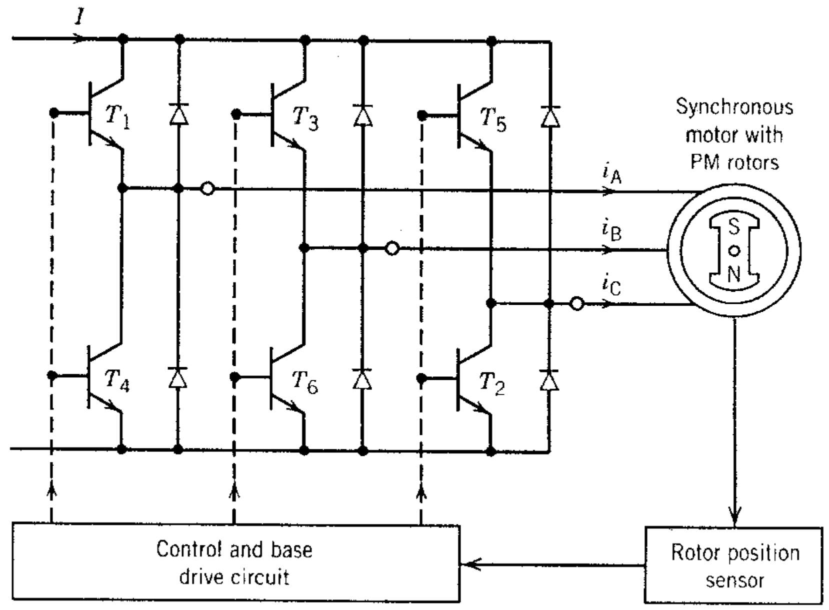


Brushless DC machine

Name may be confusing

Idea:

- PM excitation on rotor: no brushes
- mechanic commutator replaced by converter



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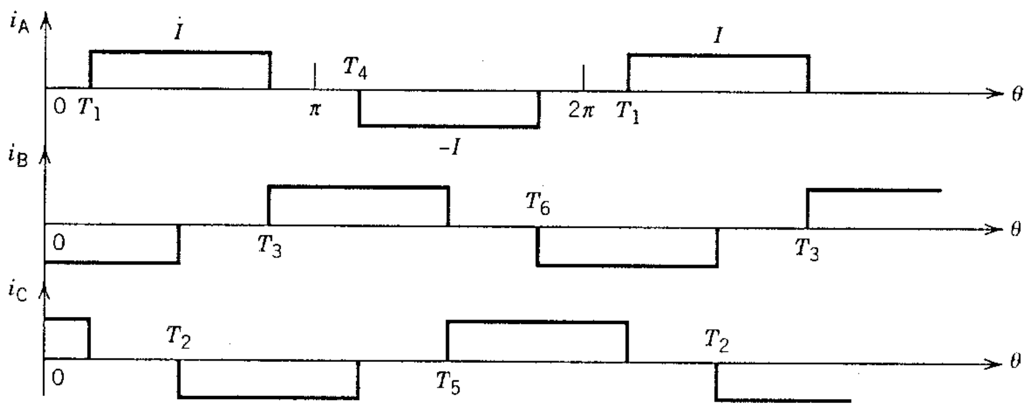
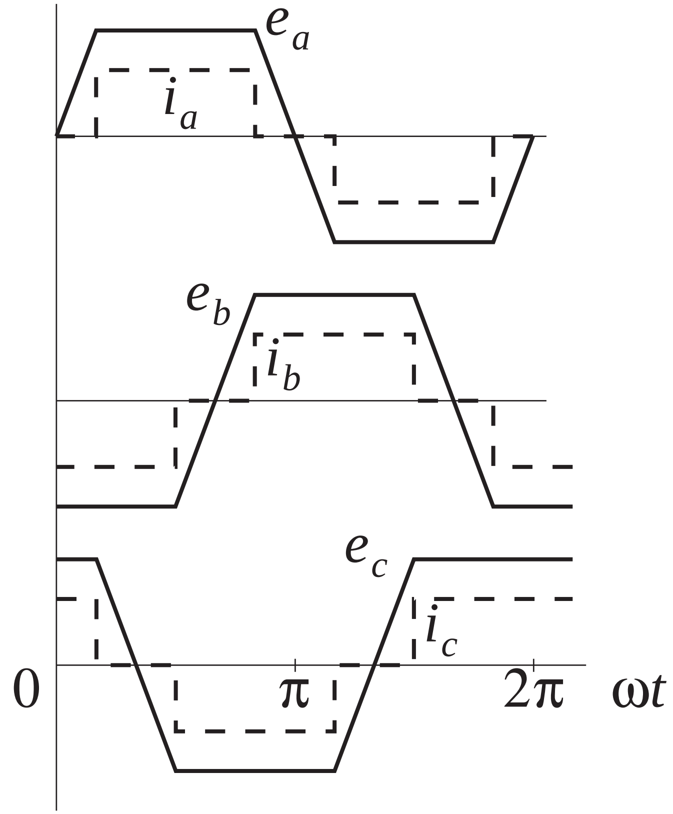
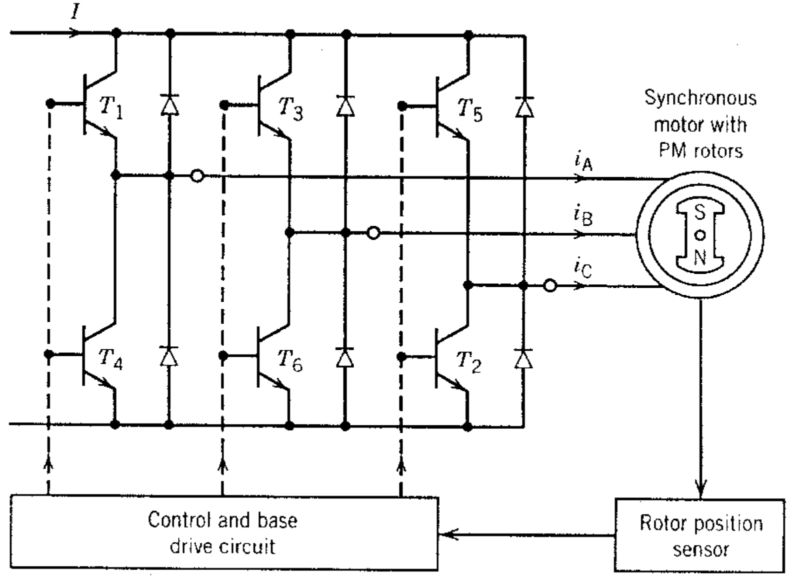


Brushless DC machine

Why trapezoidal voltage?





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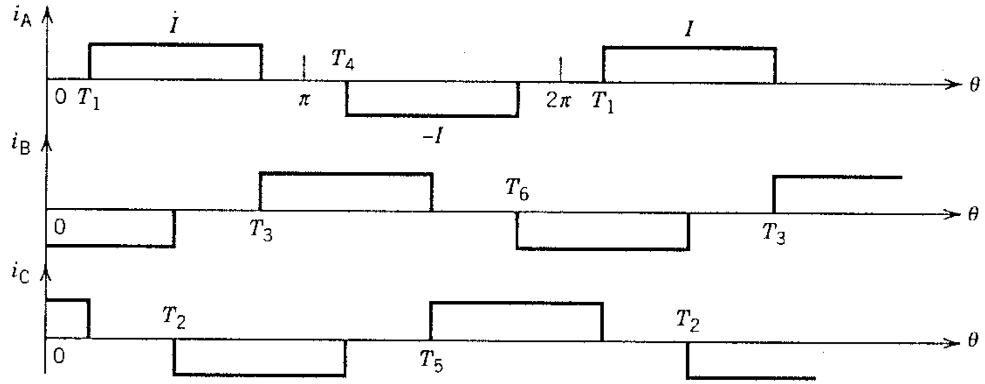
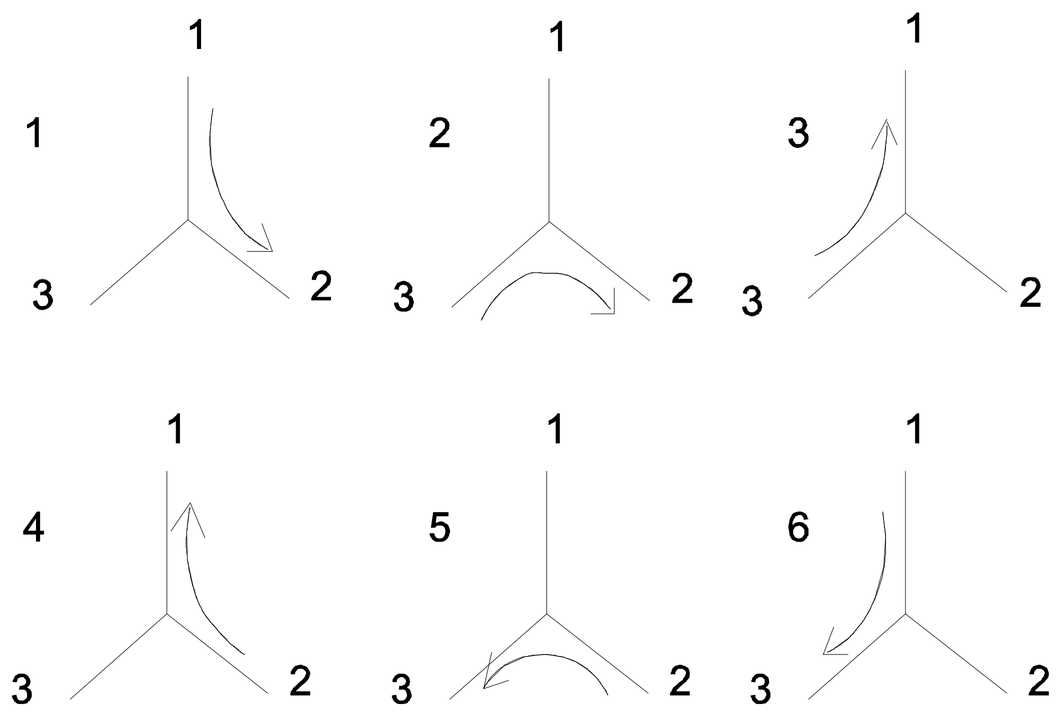


Brushless DC machine operation

- Six step operation
- Six times per revolution position information necessary



PM AC machine

For one phase without load:

$$\lambda_{\max} = NBA = N_s B_g \pi r_s l_s$$

$$E_{pm\max} = \frac{\mathrm{d}\lambda}{\mathrm{d}t} = 4f\lambda_{pm\max} = 2N_s B_g r_s l_s \omega_m$$

$$E_{pm\max} = Blv$$

BDCM voltage equations

Maxwell, Faraday: $u = Ri + \frac{\mathrm{d}\lambda}{\mathrm{d}t}$

$$\begin{cases} \lambda_{sa} = L_{sa} i_{sa} + M_{sab} i_{sb} + M_{sab} i_{sc} + \lambda_{pma}(\theta) \\ \lambda_{sb} = M_{sab} i_{sa} + L_{sa} i_{sb} + M_{sab} i_{sc} + \lambda_{pmb}(\theta) \\ \lambda_{sc} = M_{sab} i_{sa} + M_{sab} i_{sb} + L_{sa} i_{sc} + \lambda_{pmc}(\theta) \end{cases}$$

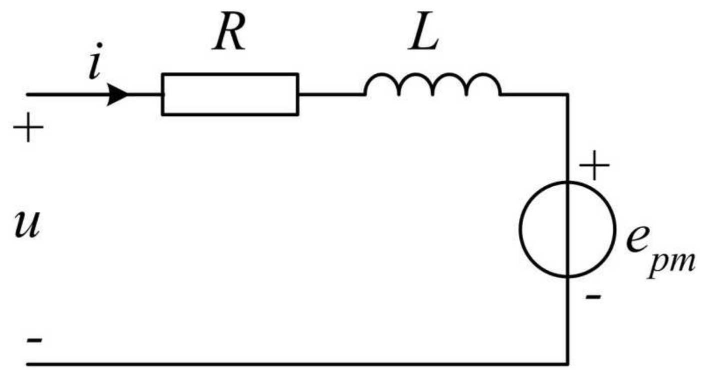
No star-point connection: $i_{sa} + i_{sb} + i_{sc} = 0$

$$L_s = L_{sa} - M_{sab}$$

$$\begin{cases} \lambda_{sa} = (L_{sa} - M_{sab}) i_{sa} + \lambda_{pma}(\theta) = L_s i_{sa} + \lambda_{pma}(\theta) \\ \lambda_{sb} = (L_{sa} - M_{sab}) i_{sb} + \lambda_{pmb}(\theta) = L_s i_{sb} + \lambda_{pmb}(\theta) \\ \lambda_{sc} = (L_{sa} - M_{sab}) i_{sc} + \lambda_{pmc}(\theta) = L_s i_{sc} + \lambda_{pmc}(\theta) \end{cases}$$

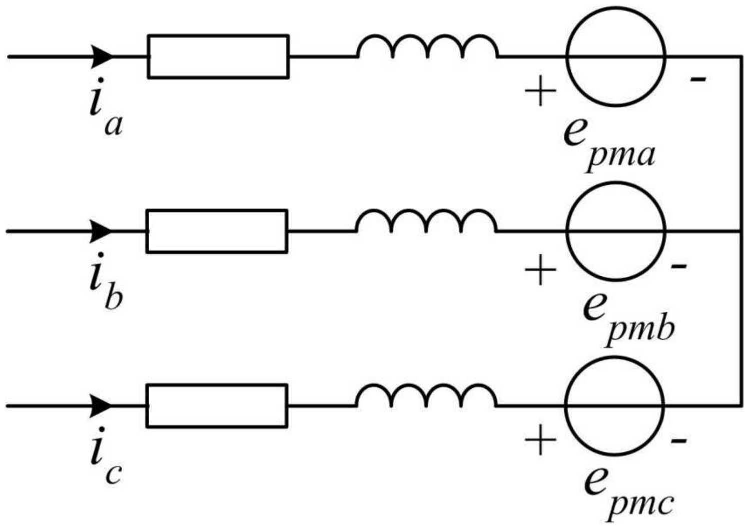
BDCM voltage equations

$$u_a = Ri_a + \frac{\mathrm{d}\lambda_a}{\mathrm{d}t}$$



Single-phase equivalent circuit

$$\begin{cases} u_a = Ri_a + L_s \dfrac{\mathrm{d}i_a}{\mathrm{d}t} + e_{pma} \\ u_b = Ri_b + L_s \dfrac{\mathrm{d}i_b}{\mathrm{d}t} + e_{pmb} \\ u_c = Ri_c + L_s \dfrac{\mathrm{d}i_c}{\mathrm{d}t} + e_{pmc} \end{cases}$$



Three-phase equivalent circuit

BDCM torque

Always two phases conducting:

$$P = u_x i_x + u_y i_y = 2RI^2 + 2\frac{\mathrm{d}\,\tfrac{1}{2}L_s I^2}{\mathrm{d}t} + 2E_{pm\max} I$$

Electrical input power = Losses + Increase stored energy + Mechanical output power

Torque:

$$T = \frac{P}{\omega_m} = \frac{2IE_{pm\max}}{\omega_m} = 4B_g N_s l_s r_s I$$

$$T = r_s F = r_s BlI$$

Power balance gives same result as Lorentz

BDCM pros and cons

- Main problem:
  - Six times per period irregularities in the torque because
    - Hall sensors different and positioned with limited accuracy
    - Motor coils are slightly different
    - The EMF (voltage induced by magnets) are different
    - Controller branches are different
    - Current can not be a square wave. Why not?
  - Consequences
    - Not nice for position servo
    - Can be improved by hysteresis in Hall sensors
- Strengths BDCM
  - Simple controller with six step position sensor
  - Sensorless operation possible at higher speeds.

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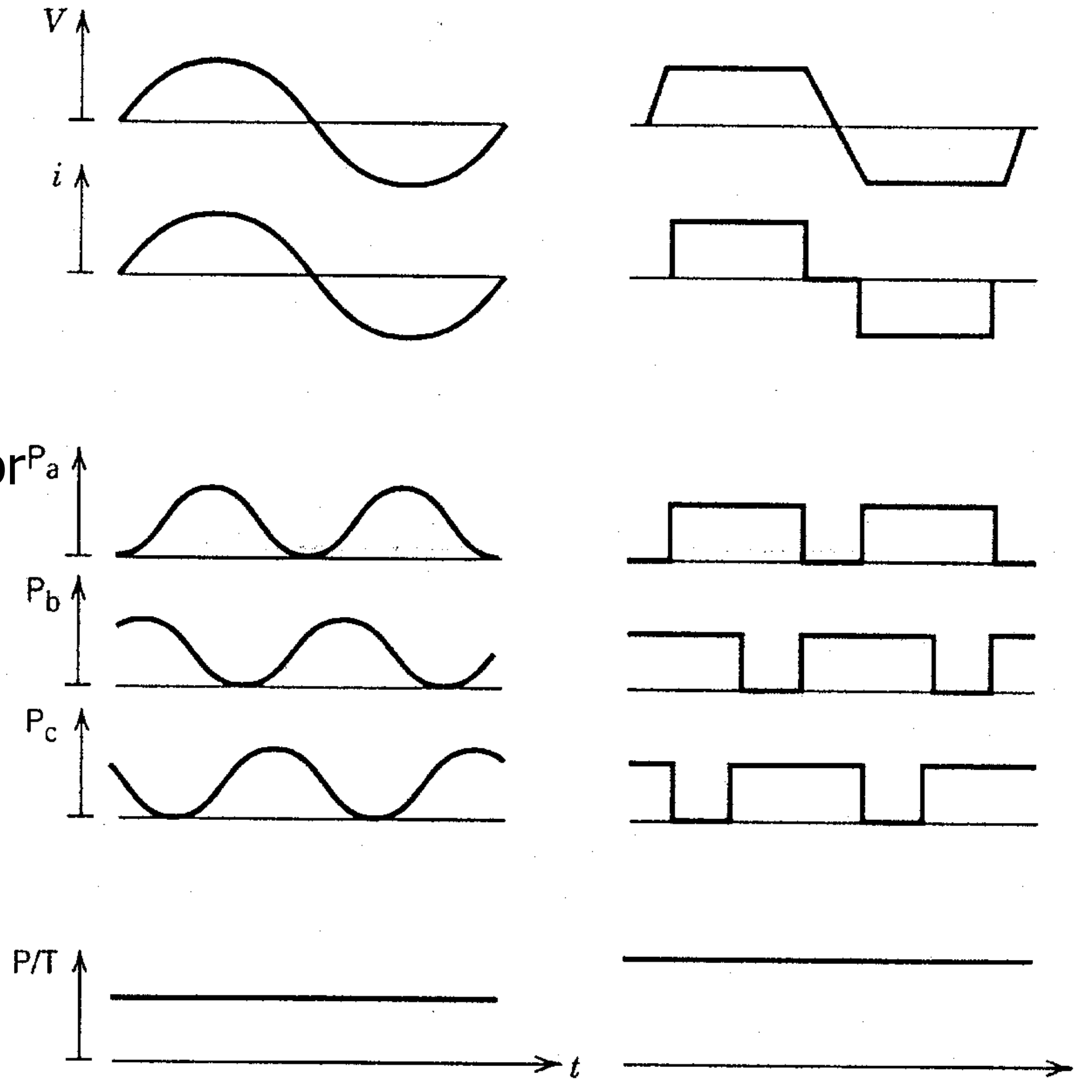
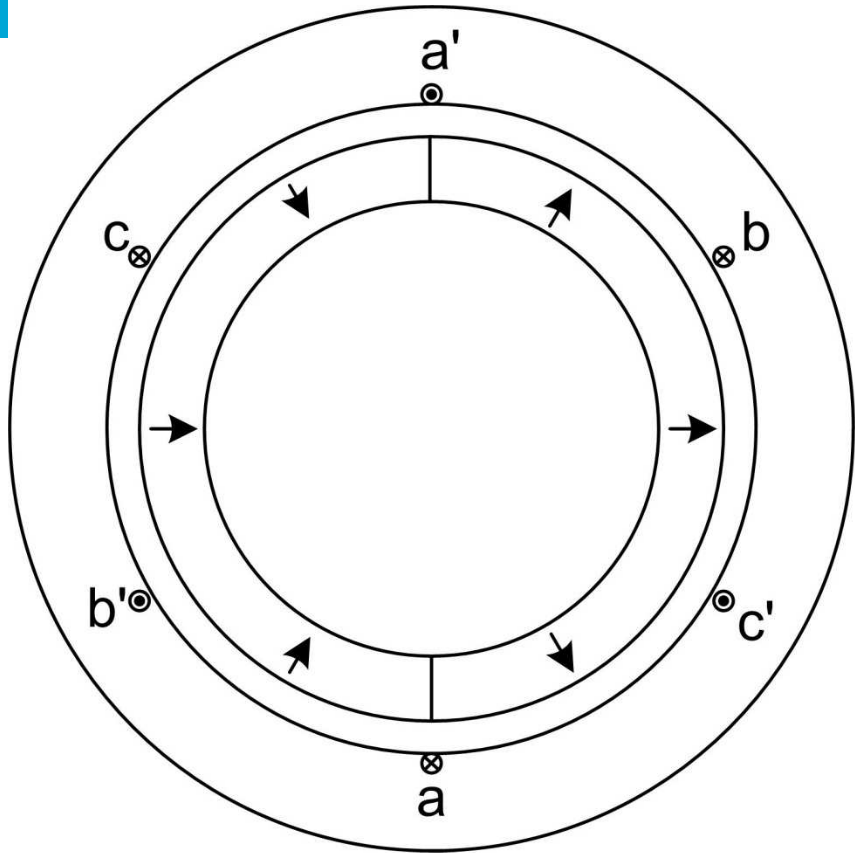
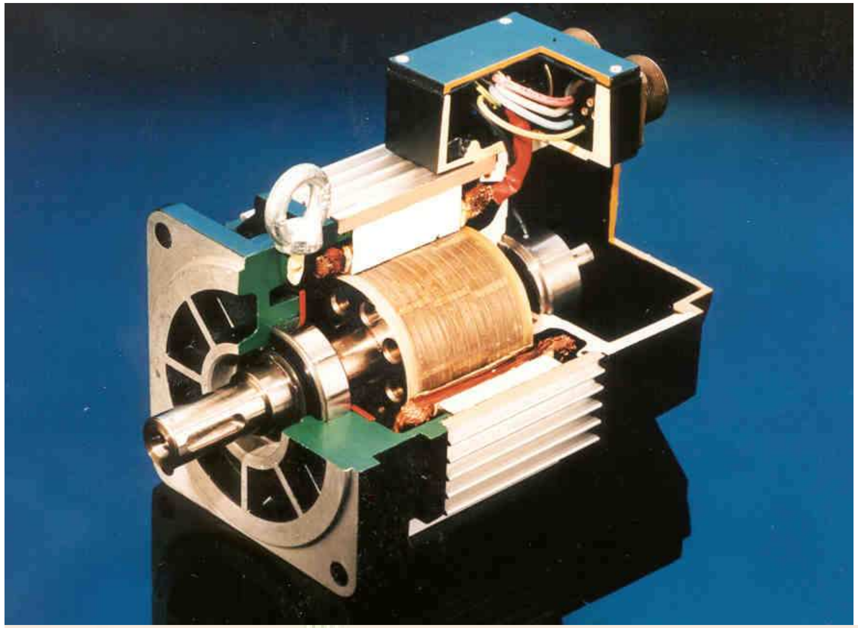
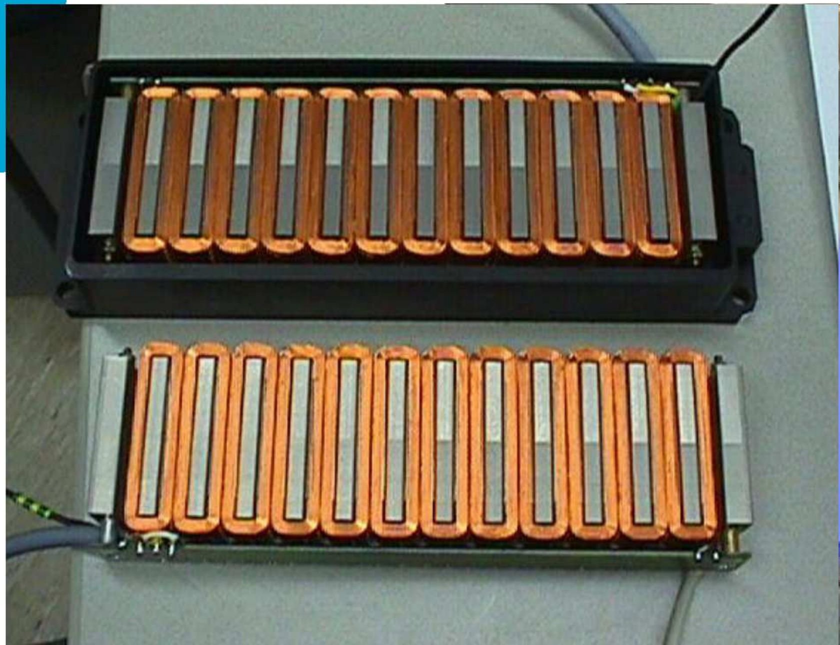


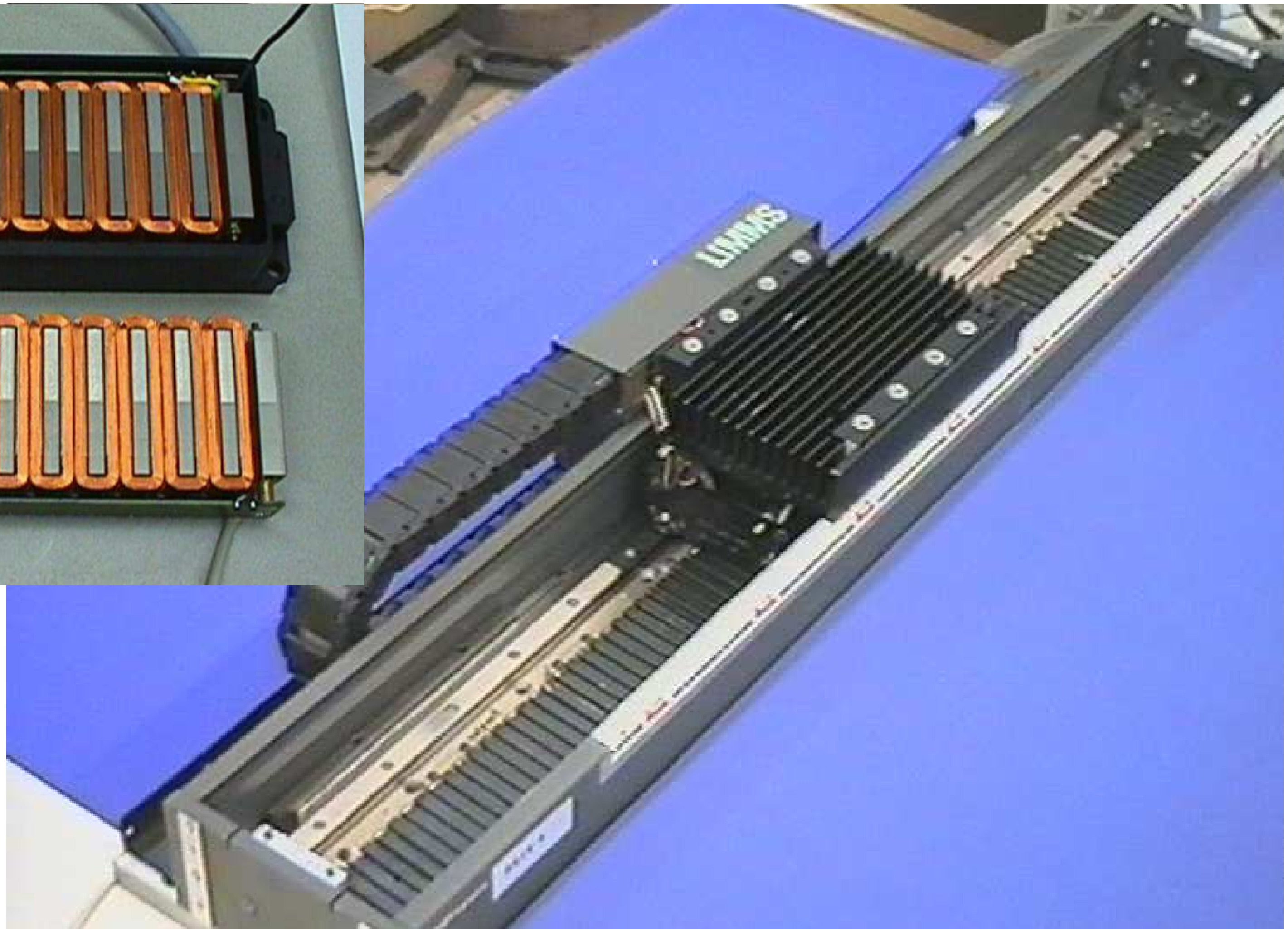
PM AC machine





PM synchronous machine





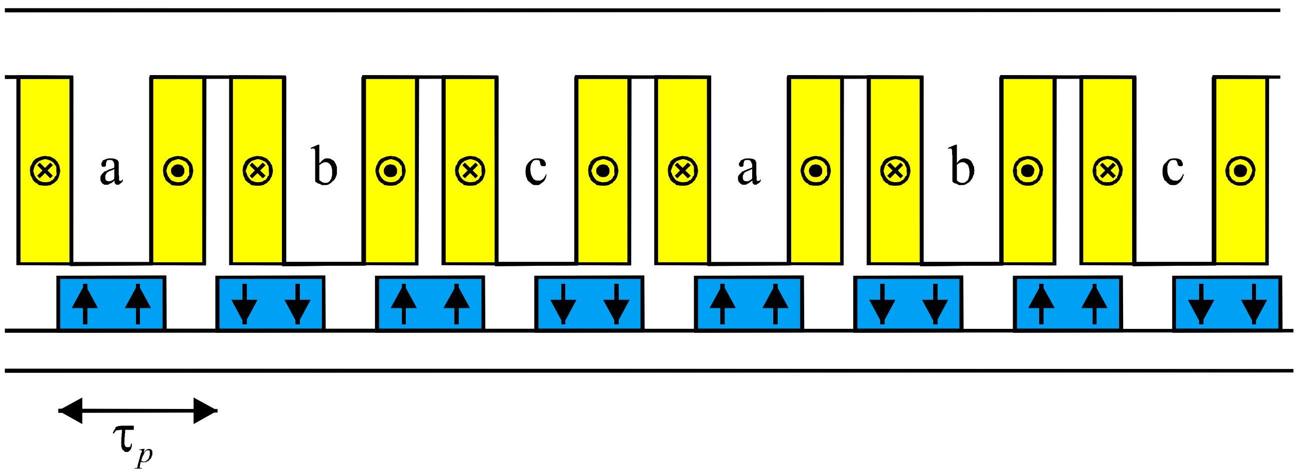
PM synchronous machine

$$\begin{cases} \Phi_{pma} = -\hat{\Phi}_{pm} \cos(\frac{\pi}{\tau_p} x) \\ \Phi_{pmb} = -\hat{\Phi}_{pm} \cos(\frac{\pi}{\tau_p} x - \frac{2}{3}\pi) \\ \Phi_{pmc} = -\hat{\Phi}_{pm} \cos(\frac{\pi}{\tau_p} x - \frac{4}{3}\pi) \end{cases}$$

Cosinusoidal because of

- skewing
- end teeth

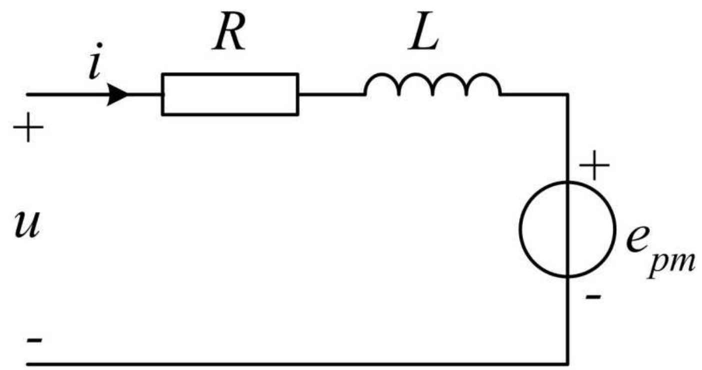
How can the voltage be calculated?



PMSM voltage equations

$$u_a = Ri_a + \frac{\mathrm{d}\lambda_a}{\mathrm{d}t}$$

$$\lambda_a = L_{sa} i_a + M_{sab} i_b + M_{sab} i_c + N\Phi_{pma}$$



Single-phase equivalent circuit

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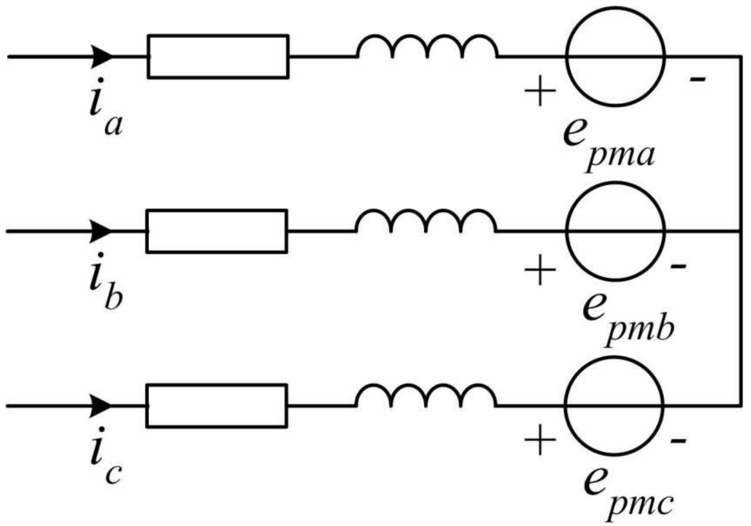


Three-phase equivalent circuit

PMSM voltage equations

$$\lambda_a = L_{sa} i_a + M_{sab} i_b + M_{sab} i_c + N\Phi_{pma}$$
$$= L_s i_a + N\Phi_{pma}$$

$$\Phi_{pma} = -\hat{\Phi}_{pm} \cos(\tfrac{\pi}{\tau_p} x)$$

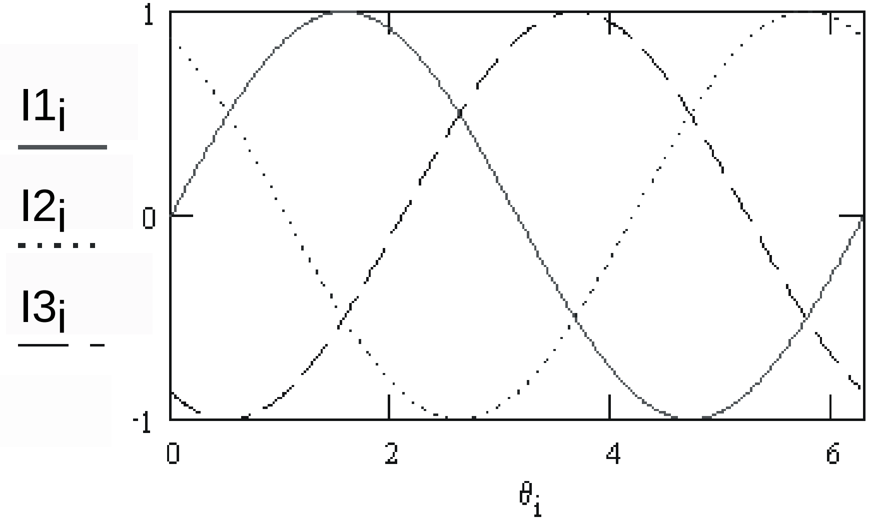
$$\begin{cases} u_a = R i_a + L_s \dfrac{\mathrm{d} i_a}{\mathrm{d} t} + e_{pma} \\ u_b = R i_b + L_s \dfrac{\mathrm{d} i_b}{\mathrm{d} t} + e_{pmb} \\ u_c = R i_c + L_s \dfrac{\mathrm{d} i_c}{\mathrm{d} t} + e_{pmc} \end{cases}$$

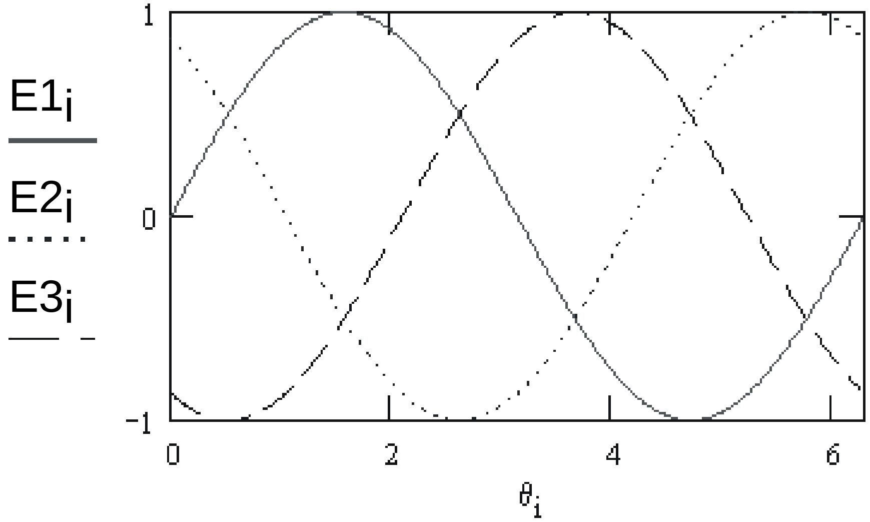
$$\begin{cases} e_{pma} = \hat{e}_{pm} \sin(\tfrac{\pi}{\tau_p} x) \\ e_{pmb} = \hat{e}_{pm} \sin(\tfrac{\pi}{\tau_p} x - \tfrac{2}{3}\pi) \\ e_{pmc} = \hat{e}_{pm} \sin(\tfrac{\pi}{\tau_p} x - \tfrac{4}{3}\pi) \end{cases}$$

What should be the current phase to make maximum force?

PMSM currents

$$\begin{cases} i_a = \hat{i}\sin(\frac{\pi}{\tau_p}x) \\ i_b = \hat{i}\sin(\frac{\pi}{\tau_p}x - \frac{2}{3}\pi) \\ i_c = \hat{i}\sin(\frac{\pi}{\tau_p}x - \frac{4}{3}\pi) \end{cases}$$





PMSM power and force

$$p = u_a i_a + u_b i_b + u_c i_c$$

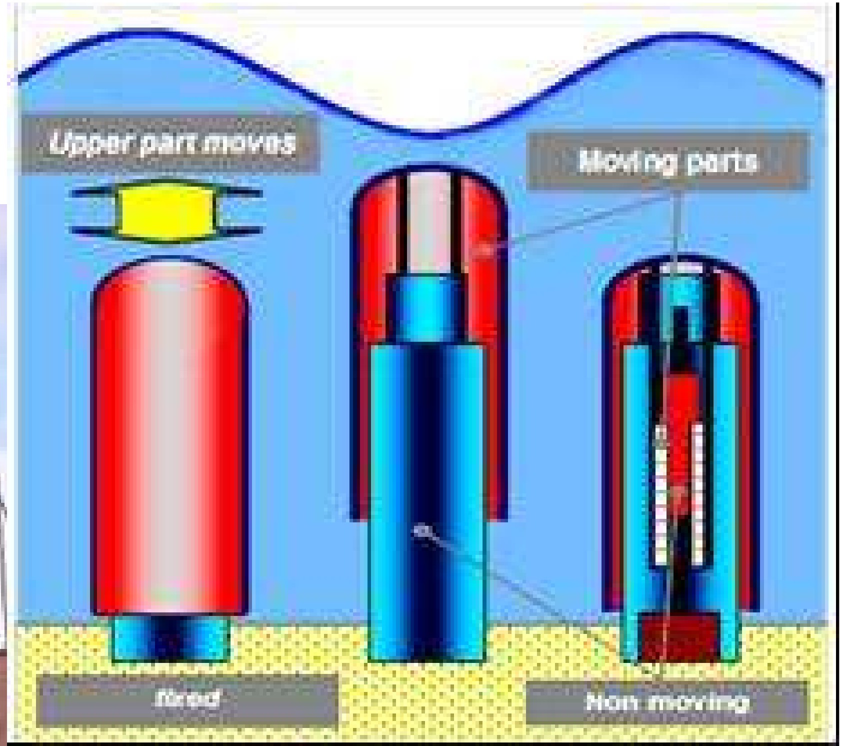
$$p = Ri_a^{\ 2} + Ri_b^{\ 2} + Ri_c^{\ 2} + \frac{\mathrm{d}\,\frac{1}{2}L(i_a^{\ 2} + i_b^{\ 2} + i_c^{\ 2})}{\mathrm{d}t} + e_{pma} i_a + e_{pmb} i_b + e_{pmc} i_c$$

$$p = \frac{3}{2} R\hat{i}^{\ 2} + \frac{\mathrm{d}W_f}{\mathrm{d}t} + \frac{3}{2}\hat{e}_{pm}\hat{i} = p_{Cu} + p_f + p_{mech}$$

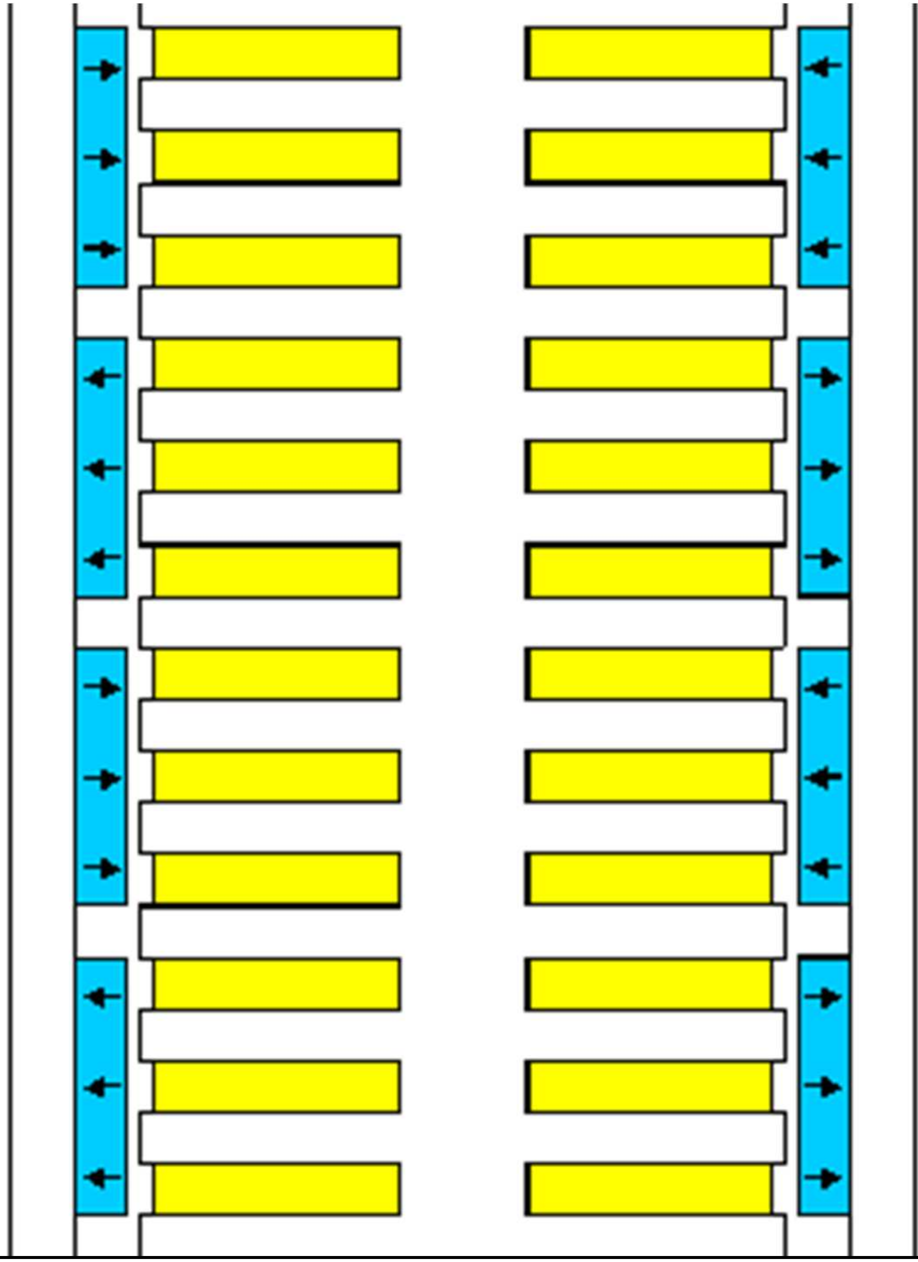
Maximum three-phase force: $F = \frac{p_{mech}}{v} = \frac{3\hat{e}_{pm}\hat{i}}{2v} = \frac{3}{2}\frac{\pi}{\tau_p} N\hat{\Phi}_{pm}\hat{i}$

Voltage $\hat{u} = \sqrt{(R\hat{i} + \omega N\hat{\Phi}_{pm})^2 + (\omega L\hat{i})^2}$ $\omega = \frac{\pi}{\tau_p}\frac{\mathrm{d}x}{\mathrm{d}t}$

Example: Archimedes Wave Swing

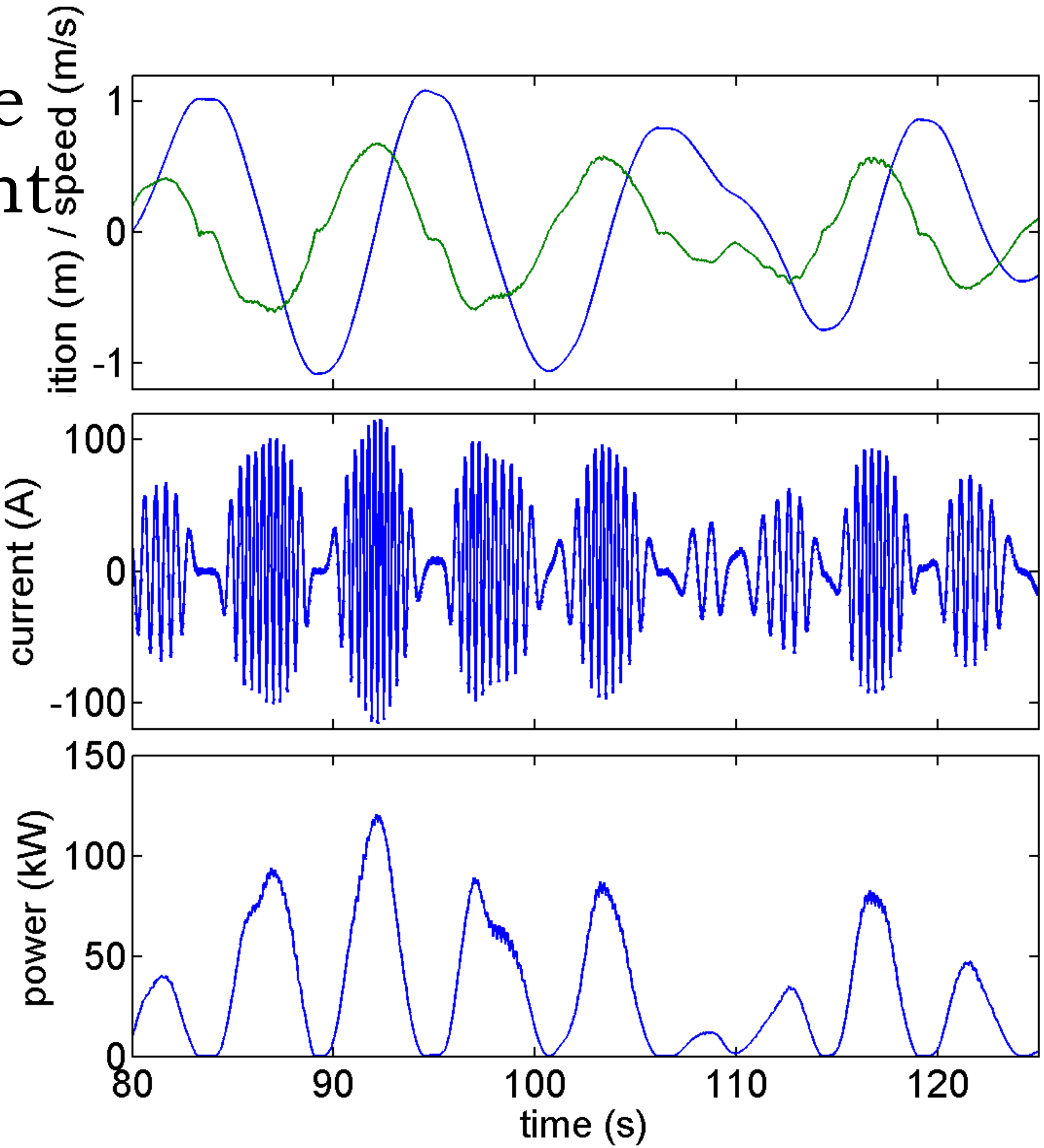


Linear AWS generator



Linear generator AWS

Measurement



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