EEEN313/ECEN405

Introduction to Motors

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Electricity vs Magnetism

ELECTRICITY		MAGNETISM	
Field	E [V/m]	Field	H [A/m]
EMF	$\mathcal{E} = \int E{\cdot}dl$ [V]	MMF	$\mathcal{F} = \int H{\cdot}dl = N \cdot Im$ [A·turn]
Current	I [A]	Flux	ϕ [Wb]
Ohm's Law	$\mathcal{E} = RI$	Rowland's Law	$\mathcal{F} = \mathcal{R}_m\Phi$
Resistance	R [Ω]	Reluctance	$\mathcal{R}_m$ [H^{-1}]
Conductance	$G=1/R$ [Ω^{-1}]	Permeance	$\mathcal{P}=1/\mathcal{R}_m$ [H]
Current Density	J=σE [A/m^2]	Flux density	$B = \mu H$ [Wb/m^2] or [T]
Conductivity	σ [$\Omega^{-1}.m^{-1}$]	Permeability	μ [H/m]

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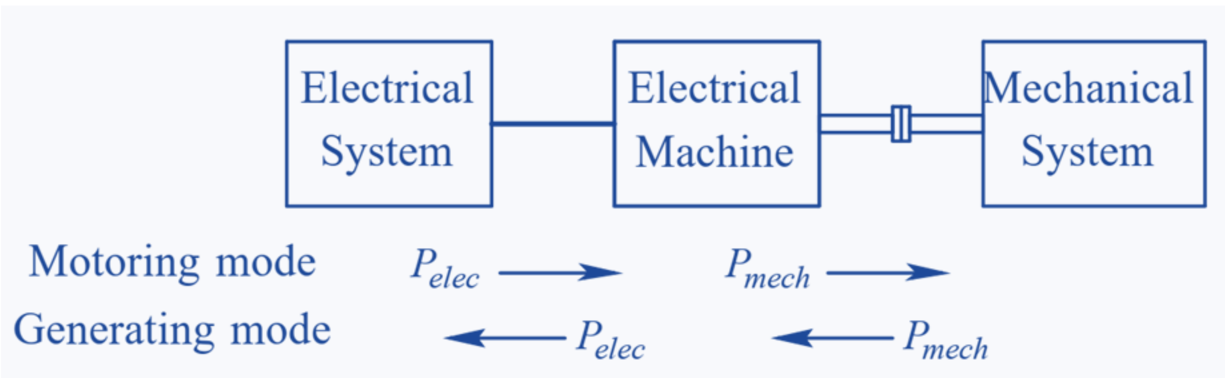
Electric Drive Conversion



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Form of Motors

- DC Motors – mostly used in low power –toys, UAVs, Robots, sliding doors
- Large DC motors exist but seldom used – EVs are moving away from DC motors
- AC motors are most used – Induction Motors, Synchronous Motors (Single and 3 phase)
- Induction motors are work horses – simple, efficient, reliable
- Your refrigerators, heat pumps, fans –all use IM
- So lets look at Induction Motor first!

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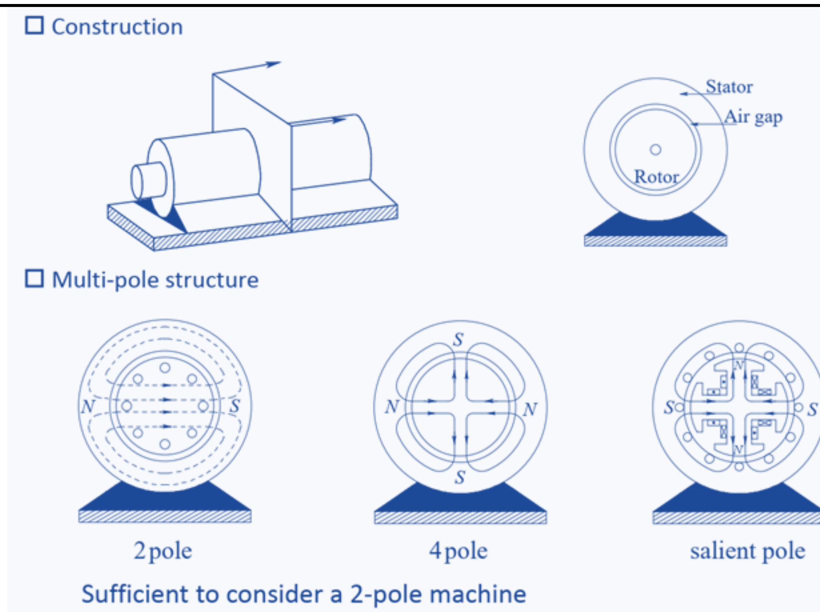
Poles



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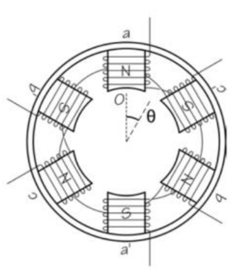
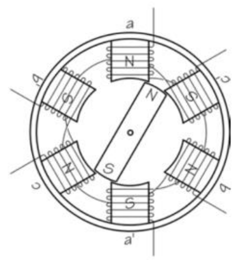
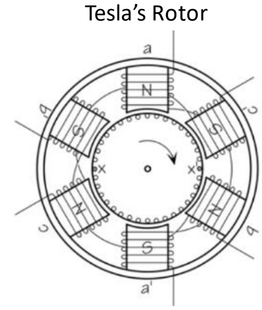
Tesla's motor (not the car)

Tesla's Rotor





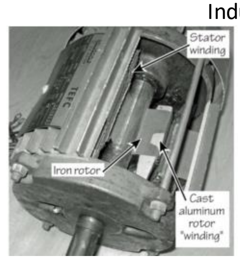


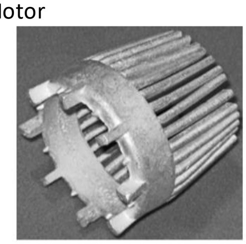
$$\phi_{total} = \frac{3}{2} kI \cos(\omega t - \theta)$$

Now add rotor

Synchronous motor

Induction Motor





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Slip – Motor speed

- At 50 Hz, the maximum motor speed is 3000 rpm (for a two pole motor).
- If the rotor winding rotates at same speed as rotating field, it sees no changing flux – so no induced current – no rotor field – no torque.
- So no ‘going’ at same speed as rotating field.
- Hence the introduction of slip

$$s = \frac{n_s - n_m}{n_s}$$

Normally less than 5%

- We can build IMs with any number of poles provided they are multiples of 6.

$$n_s = \frac{60 f}{p/2}$$

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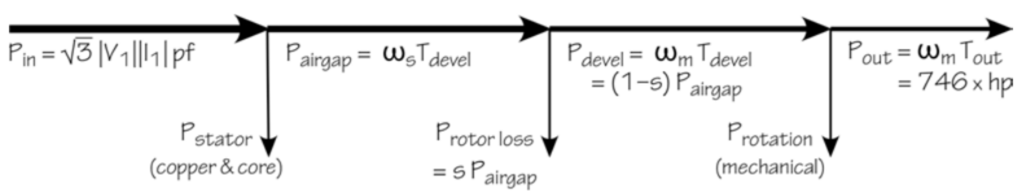
Power Flow through Induction Motor

- Power flow through an IM – input power to output shaft



- 3 phase power input – voltage is line voltage
- Stator loss due to wire heating and reversing magnetic domains of the core
- Rest goes to airgap and crosses to rotor

$$\omega_s = \frac{n_s}{60} 2\pi$$

This is synchronous speed
Not actual rotor speed

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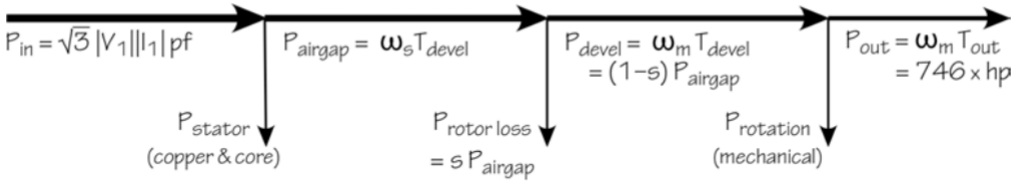

- Power lost in rotor is proportional to the slip – wire and core losses
- Rest goes to shaft of the motor – power is developed torque related to speed of the shaft

$$\omega_m = \frac{n_m}{60} 2\pi$$

- Remaining loss is mechanical due to windage and bearing loss
- Efficiency > 85%

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Losses and Efficiency

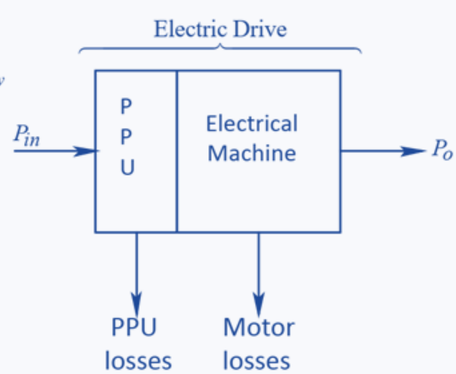
- Motor losses
  - Conduction losses, P_R
  - Iron losses, P_{he}
  - Friction and windage losses, P_{fw}
  - Switching losses, P_{sw}
  - Stray losses, P_s

$$P_{loss} = P_R + P_{he} + P_{sw} + P_{fw} + P_s$$

$$\eta_{mach} = \frac{P_o}{P_{in}} = \frac{Po}{P_o + P_{loss}}$$

- PPU losses
  - Conduction losses
  - Switching losses

$$\eta_{drive} = \eta_{PPU} \times \eta_{motor} \qquad (80-90\%)$$



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Basic Principles

- ☐ Assumptions
  - Uniform B_s , radial in direction
  - Rotor current of constant magnitude but direction changes with position
  - counter-clockwise torque is positive
- ☐ Force acting on the conductor

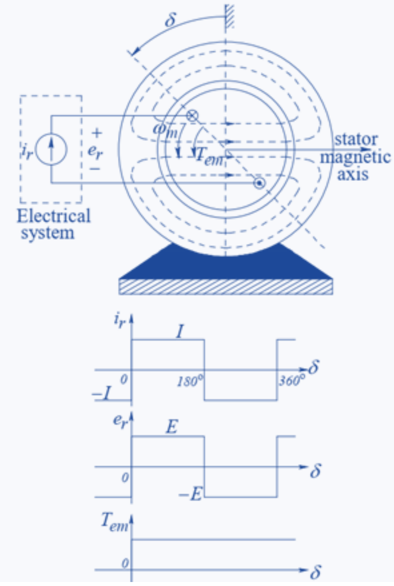
  $$f_{em} = B_s(N_r I)l$$

  and torque on coil

  $$T_{em} = 2 f_{em} r = 2B_s(N_r I)lr$$

  torque remains constant as rotor turns
- ☐ emf induced in coil

  $$e_r = 2e_{cond} = 2N_r B_s l_r \omega_m r$$



Motoring Mode

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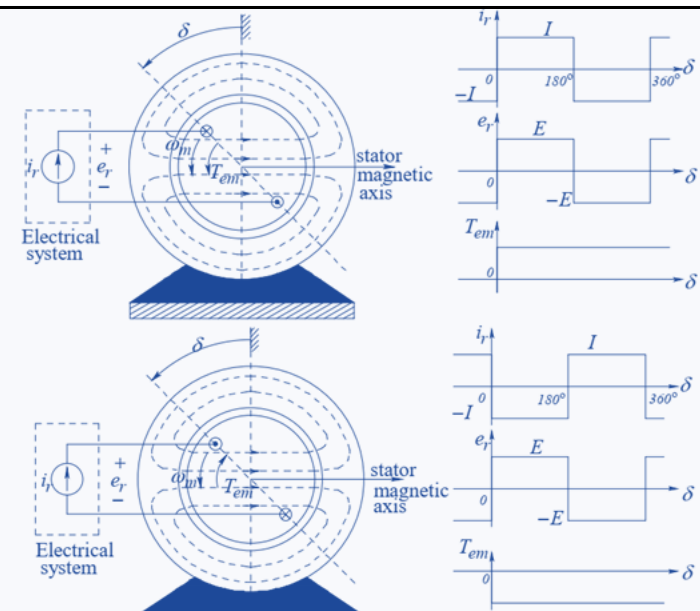
Two Modes

Motoring Mode

Regenerative braking Mode



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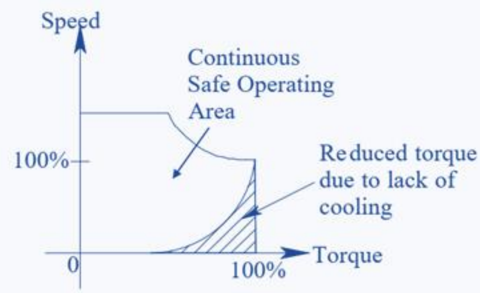
Motor Ratings

- ☐ Safe Operating Area



- ☐ Rated speed, torque and power $P_{rated} = \omega_{rated} T_{rated}$
- ☐ Motor temperature rise due to losses
- ☐ Expanded safe operating area during transients and for intermittent operation

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An Example

- Specifications for a 10-hp 60 Hz totally-enclosed three-phase induction motor in a particular manufacturer's catalogue show voltage as 208-230/460V, current as 28.0-25.0/12.5 A, Power Factor is 83.5%, Efficiency is 88.5%, full-load speed 1,740 rpm. Calculate the following:
- Power Output: $\mathrm{P}_{out} = 10\ \mathrm{hp} \times 746\ \mathrm{W/hp} = 7.46\ \mathrm{kW}.$
- Power Input: $\mathrm{P}_{in} = \sqrt{3} \times 460 \times 12.5 \times 0.835 = 8.316\ \mathrm{kW}.$
- Efficiency: $\%\eta = 100(7.46/8.316) = 89.7\%,$
- Number of Poles: The full-load speed is 1,740 rpm, which is just under 1,800 rpm. So the motor has four poles because $\mathrm{n}_s = 3600/(p/2) = 1800$ for $\mathrm{p} = 4.$

$$\text{Slip: } \mathrm{s} = 100(1800 - 1740)/1800 = 3.33\%.$$

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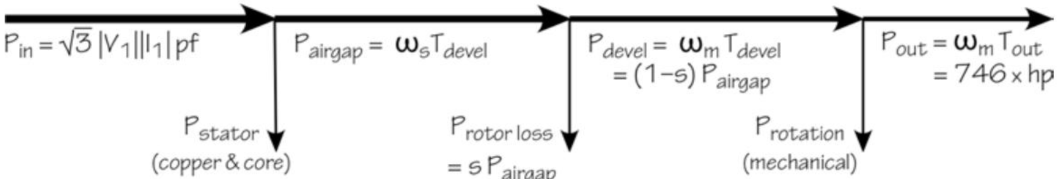
Exmple Contd…



Developed power, assuming windage if windage and bearing losses are 200 W: $\mathrm{P}_{devel} = 7.46 + 0.2 = 7.66$ kW.

Air-gap power: $\mathrm{P}_{airgap} = 7.66/(1-s) = 7.66/(1-0.333) = 7.924$ kW.

Rotor loss: $\mathrm{P}_{rotor} = \mathrm{P}_{airgap} - \mathrm{P}_{devel} = 7.924 - 7.66 = 264$ W.

Stator loss: $\mathrm{P}_{stator} = \mathrm{P}_{in} - \mathrm{P}_{airgap} = 8.316 - 7.924 = 392$ W.

Output torque: $\omega_m = (1740/60)2\pi = 182.2$ radians/second, so $\mathrm{T}_{out} = \mathrm{P}_{out}/\omega_m = 40.94$ N-m.

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