ECE330: Power Circuits & Electromechanics

Lecture 23. Induction machine torque-speed characteristics

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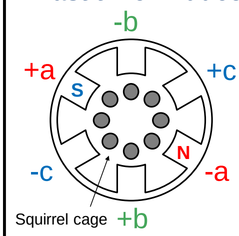
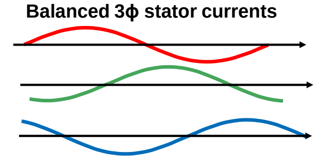
1

1

Last time: Induced currents





Stator field at synchronous speed

But spins at reduced speed

Rotor construction?

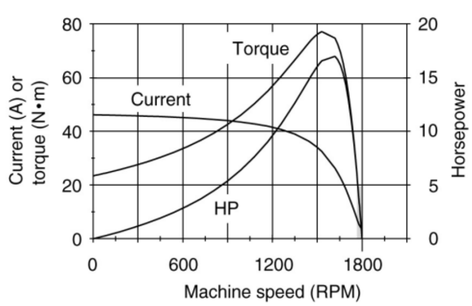
Nonmagnetic conductor → Induction machine

Cheap, rugged, reliable, but quite complicated and historically difficult to squeeze maximum performance

2

2

Today: Figure out how to drive this thing



http://electricalacademia.com/induction-motor/torque-speed-characteristics-induction-motor/

3

3

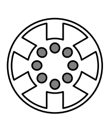
Today

- Review: Induction machine model
- Starting torque and no-slip torque
- Torque-speed characteristics
- Example problems

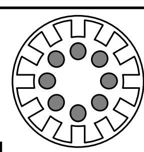
4

4

Recall: Poles, Mechanical Speed, Slip, Torque



2 pole



4 pole

Mechanical / Electrical

$$\omega_m = \frac{2}{p}(\omega_s - \omega_r)$$

Mech Speed [rad/s] — Stator frequency [rad/s] — Rotor frequency [rad/s]

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

Slip [Dimensionless]

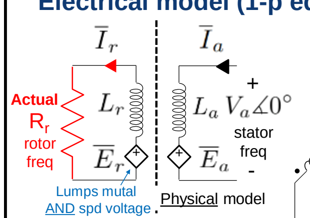
Same idea behind torque as sync mach

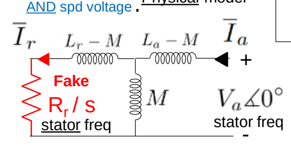
$$\boxed{\text{Torque [Nm]} = \frac{\text{Mechanical power [W]}}{\text{Mechanical speed [rad/s]}}}$$

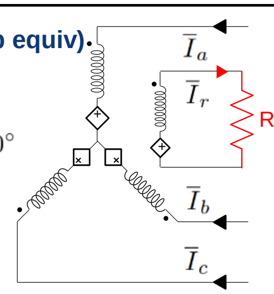
5

5

Electrical model (1-p equiv).







Issue: Rotor currents hard to compute!

Solution: Transformer equivalent circuit

6

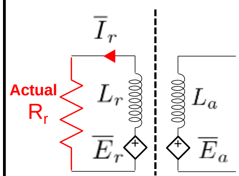
6

Power transfer

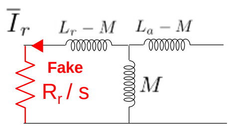
Elec. Input → Stator winding loss → Stator core loss → Power across gap $\frac{3}{s}|\bar{I}_r|^2 R_r$ → Rotor winding loss $3|\bar{I}_r|^2 R_r$ → Mech. Output $\frac{3(1-s)}{s}|\bar{I}_r|^2 R_r$

Efficiency $\approx 1 - s$

Drives the torque



Physical model



Computational tool

7

7

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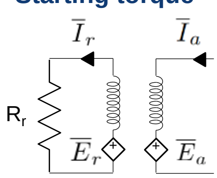
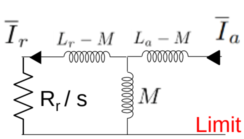
8

8

Starting torque





Mechanical power input
(drives the torque)

$$3|\bar{I}_r|^2 R_r (1-s)/s$$

What happens if ωm = 0?

A) $T_e = 0$; B) $T_e = \infty$; C) T_e finite

Mechanical speed

$$\omega_m = \frac{2}{p}(\omega_s - \omega_r) = \frac{2}{p}(1-s)\omega_s$$

Torque = Power / Speed

$$T_e = \frac{P_m}{\omega_m} = \frac{p}{2}\frac{(1-s)P_{ag}}{(1-s)\omega_s}$$

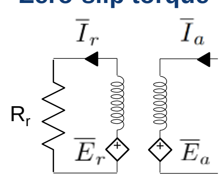
Limit of zero divided by zero

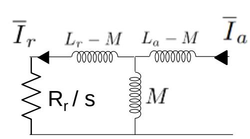
$$= 3\left(\frac{p}{2}\right)\left(\frac{|\bar{I}_r|^2 R_r}{s \cdot \omega_s}\right)$$

9

9

Zero-slip torque





Mechanical power input
(drives the torque)

$$3|\bar{I}_r|^2 R_r (1-s)/s$$

What about ωm = ωs?

A) $T_e = 0$; B) $T_e = \infty$; C) T_e finite

Mechanical speed

$$\omega_m = \frac{2}{p}(\omega_s - \omega_r) = \frac{2}{p}(1-s)\omega_s$$

Torque = Power / Speed

$$T_e = \frac{P_m}{\omega_m} = 0$$

Limit of zero divided by finite

10

10

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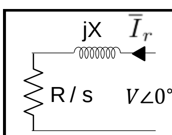
11

11



Assume:

- v(t) = V cos(ω_st)
- Constant V, say 120V
- Constant ω_s, say 120π for 60Hz
- Two-pole machine

$$|\bar{I}_r|^2 = \frac{|\bar{V}_a|^2}{(R/s)^2 + X^2} = \frac{V^2}{R^2}\frac{s^2}{1 + s^2\tan^2\phi}$$

$$P_{ag} = 3|\bar{I}_r|^2 R/s = \frac{3V^2}{R}\frac{s}{1+s^2\tan^2\phi}$$

$$P_{cu} = 3|\bar{I}_r|^2 R = sP_{ag}$$

$$P_m = P_{ag} - P_{cu} = \frac{3V^2}{R}\frac{(1-s)s}{1+s^2\tan^2\phi}$$

$$T_e = \frac{P_m}{\omega_m} = \frac{(1-s)P_{ag}}{(1-s)\omega_s} = \frac{P_{ag}}{\omega_s} = \frac{3V^2}{R\omega_s}\frac{s}{1+s^2\tan^2\phi}$$

12

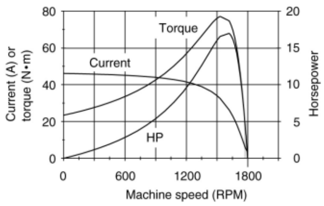
12

Torque-speed curve

$$T^e = \frac{3V^2}{R\omega_s}\frac{s}{1+s^2\tan^2\phi}$$

$$I = \frac{V^2}{R^2}\frac{s^2}{1+s^2\tan^2\phi}$$

$$P_m = \frac{3V^2}{R}\frac{(1-s)s}{1+s^2\tan^2\phi}$$



http://electricalacademia.com/induction-motor/torque-speed-characteristics-induction-motor/

Theorem. Max torque at

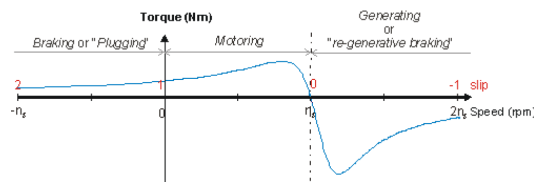
$$s = \frac{\pm 1}{\tan\phi}$$

Proof: Differentiate T^e against s

13

13

Torque-speed curve over a wider range



$$T^e = \frac{3V^2}{R\omega_s}\frac{s}{1+s^2\tan^2\phi}$$

https://people.ucalgary.ca/~aknigh/electrical_machines/induction/im_trq_speed.html

14

14

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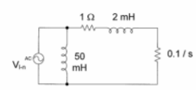
15

15

Sp06

A four-pole induction motor with the approximate equivalent circuit shown below is operated from 240 V (line-to-line), 60 Hz, three-phase power. Rated speed is 1760 RPM.



(a) Find mechanical power at rated slip, in horsepower (1 hp = 746 W) (5 pts).

16

16

Sp03

A 230 Volt (line to line), 6-pole, 3-phase, 60Hz, balanced, symmetrical, round-rotor induction machine has negligible stator copper loss, negligible core loss, and negligible stator leakage reactance. The magnetizing reactance as seen on the stator side is 40 Ohms and the rotor leakage reactance as seen on the stator side is 2 Ohms. The full-load (Pm = 3,700Watts 3-phase) speed is 1050 RPM.

a) What are the rotor copper losses?

b) What is the full-load torque in Newton-Meters?

17

17