

3-Phase Induction Motors

EE 340

Where does the power go?

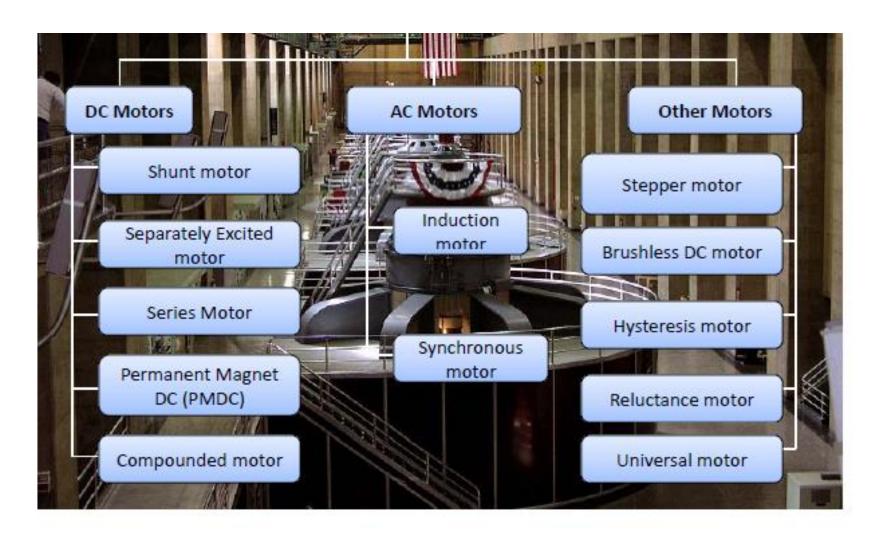
- The electric energy generated purchased by consumers for different needs. This energy is converted to different forms:
 - Lighting (indoor/outdoor CFL, incandescent, LED, Halogen...)
 - Heating (electric water heaters, clothes dryers, electric stoves and ovens)
 - power supply of electronic devices (computers, TV, DVD, battery chargers, home automation, etc...)
 - Industrial (arc furnaces, welders, manufacturing processes....)
 - Conversion to mechanical power by motors
 (pumps, fans, HVAC, refrigeration compressors, power tools, food processors, escalators, elevators,)







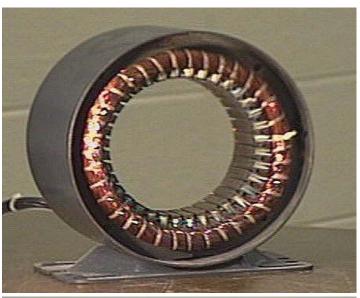
Types of Electric Motors



3-Phase induction machine construction

- 3 stator windings (uniformly distributed as in a synchronous generator)
- Two types of rotor:
 - Squirrel cage
 - Wound rotor (with slip rings)

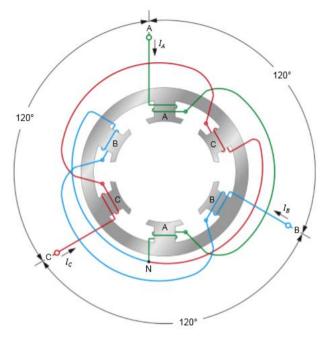


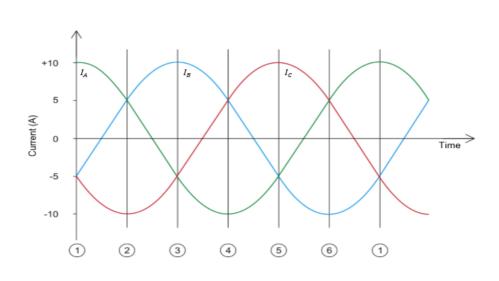


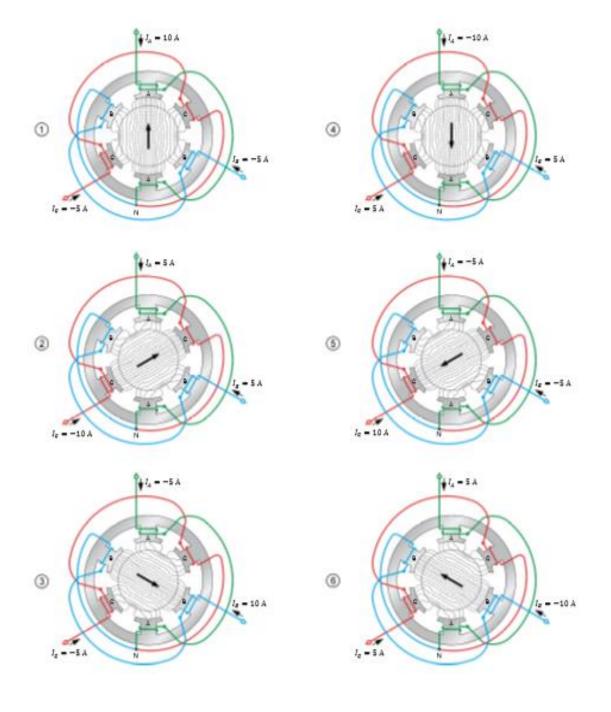


The rotating magnetic field

- The basic idea of an electric motor is to generate two magnetic fields: rotor magnetic field and stator magnetic field and make the stator field rotating. The rotor will constantly be turning to align its magnetic field with that of the stator field.
- The 3-phase set of currents, each of equal magnitude and with a phase difference of 120°, flow in the stator windings and generate a rotating field will constant magnitude.





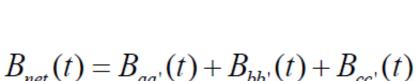


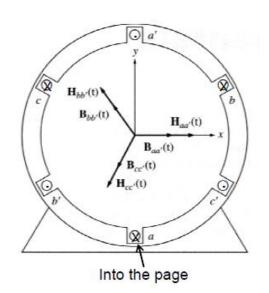
The rotating magnetic field

 Consider a two-pole. The 3-phase stator coils are placed 120° apart. Once connected to the source, the currents in three coils will be balanced and symmetrical,

$$\begin{cases} i_{aa'}(t) = I_M \sin \omega t \\ i_{bb'}(t) = I_M \sin \left(\omega t - 120^0\right) \\ i_{cc'}(t) = I_M \sin \left(\omega t - 240^0\right) \end{cases}$$

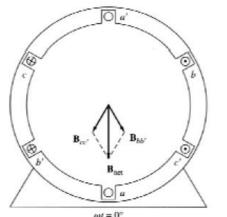
 The magnetic flux density generated by these currents stator at any arbitrary moment is given by

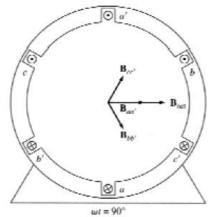


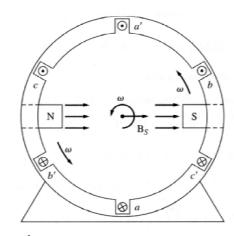


The rotating magnetic field

- The net magnetic field has a constant magnitude and rotates counterclockwise at the angular velocity ω .
- The stator rotating magnetic field can be represented by a spinning magnet.



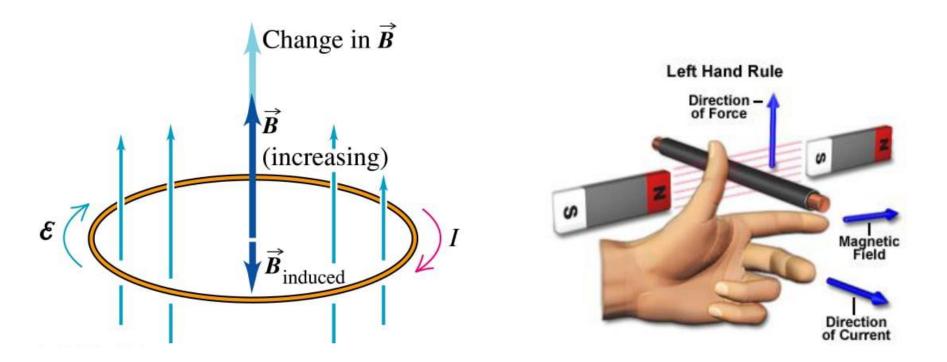




- For a two pole machine, $f_e(Hz) = f_m(rps) = \frac{1}{60}n_s(rpm)$
- For a p-pole machine, $f_e(Hz) = \frac{p}{2} f_m(rps) = \frac{p}{120} n_s(rpm)$

Principle of Operation

 https://www.electrical4u.com/workingprinciple-of-three-phase-induction-motor/



Induction motor speed

- So, the induction motor will always run at a speed lower than the synchronous speed
- The difference between the motor speed and the synchronous speed is called the slip speed

$$n_{slip} = n_{sync} - n_m$$

Where n_{slip} = slip speed n_{sync} = speed of the magnetic field n_m = mechanical shaft speed of the motor

The Slip

$$S = \frac{n_{symc} - n_m}{n_{symc}}$$

Where s is the slip

Notice that : if the rotor runs at synchronous speed

$$s = 0$$

if the rotor is stationary

$$s = 1$$

Slip may be expressed as a percentage by multiplying the above by 100. Notice that the slip is a ratio and doesn't have units.

Induction Motors and Transformers

- Both induction motor and transformer works on the principle of induced voltage
 - Transformer: voltage applied to the primary windings produce an induced voltage in the secondary windings
 - Induction motor: voltage applied to the stator windings produce an induced voltage in the rotor windings
 - The difference is that, in the case of the induction motor, the secondary windings can move
 - Due to the rotation of the rotor, the induced voltage in it does not have the same frequency of the stator voltage.

Rotor Frequency

The frequency of the voltage induced in the rotor is given by

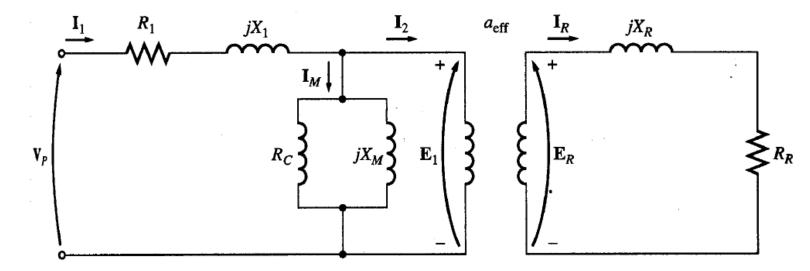
$$f_r = \frac{p.n_{slip}}{120}$$

Where f_r = the rotor frequency (Hz) p = number of stator poles n_{slip} = slip speed (rpm)

$$f_r = \frac{p(n_{syn} - n_m)}{120} = \frac{p.s.n_{syn}}{120} = sf_e$$

Equivalent Circuit

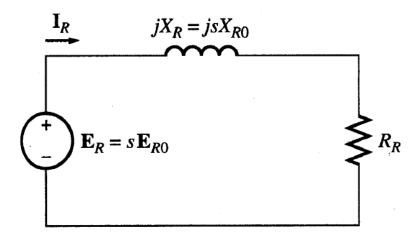
 The induction motor is similar to the transformer with the exception that its secondary windings are free to rotate



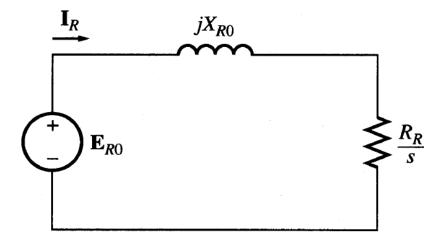
It is easier if we can combine these two circuits in one circuit but there are some difficulties:

Equivalent Circuit

Then, we can draw the rotor equivalent circuit as follows



Now we can have the rotor equivalent circuit

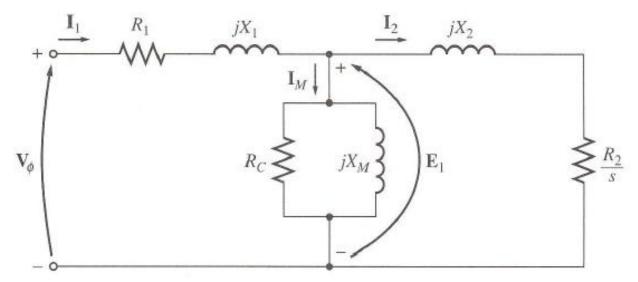


Per-phase equivalent circuit

Motor Slip

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

- R₁ and R₂: stator and rotor winding resistances
- X₁ and X₂: stator and rotor winding leakage reactances
- X_m: magnetizing reactance
- R_c: core loss resistance
- Rotor winding parameters are referred to the stator side



Power flow diagram

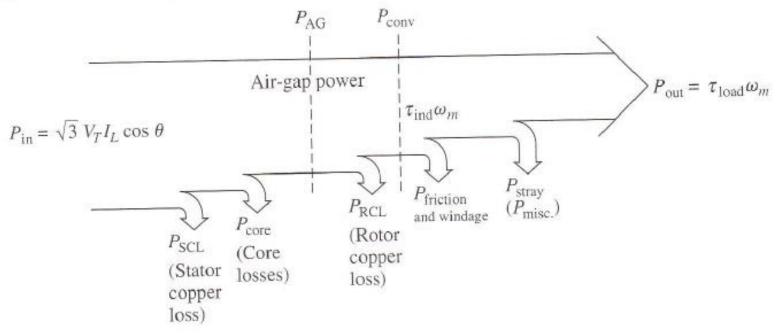
$$P_{SCL} = 3I_1^2 R_1$$

$$p_{core} = 3E_1^2 / R_C$$

$$P_{AG} = 3I_2^2 (R_2 / S)$$

$$P_{RCL} = 3I_2^2 R_2$$

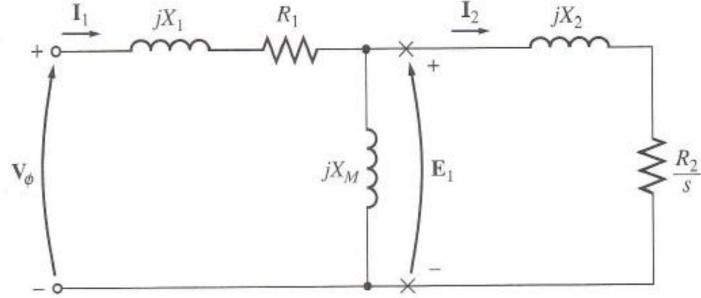
$$P_{conv} = P_{AG} - P_{RCL} = 3I_2^2 [R_2 (1 - S) / S]$$



Simplified per-phase equivalent circuit

Core loss is embedded with friction, windage and stray-load loss

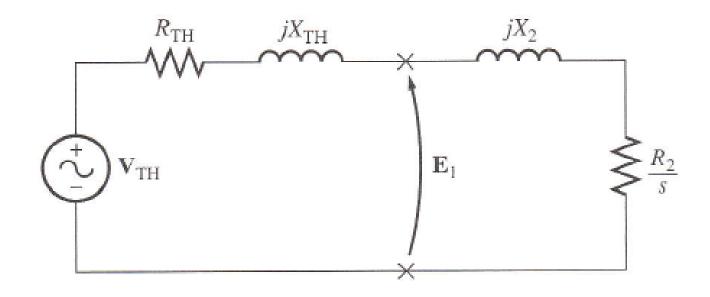
$$\begin{split} P_{SCL} &= 3I_1^2 R_1 \\ P_{RCL} &= 3I_2^2 R_2 \\ P_{AG} &= 3I_2^2 (R_2 / S) = \tau_{ind} \omega_{sync} \\ P_{conv} &= P_{AG} - P_{RCL} = 3I_2^2 R_2 (1 - S) / S = \tau_{ind} \omega_m \end{split}$$



Thevenin equivalent circuit and torque-slip equation

$$V_{TH} \approx V_{\phi} \frac{X_{M}}{X_{1} + X_{M}}, \quad X_{TH} \approx X_{1}, R_{TH} \approx R_{1} \left(\frac{X_{M}}{X_{1} + X_{M}}\right)^{2}$$

$$\tau_{ind} = \frac{P_{AG}}{\omega_{sync}} = \frac{3V_{TH}^{2}R_{2}/S}{\omega_{sync} \left[(R_{TH} + R_{2}/S)^{2} + (X_{TH} + X_{2})^{2} \right]}$$

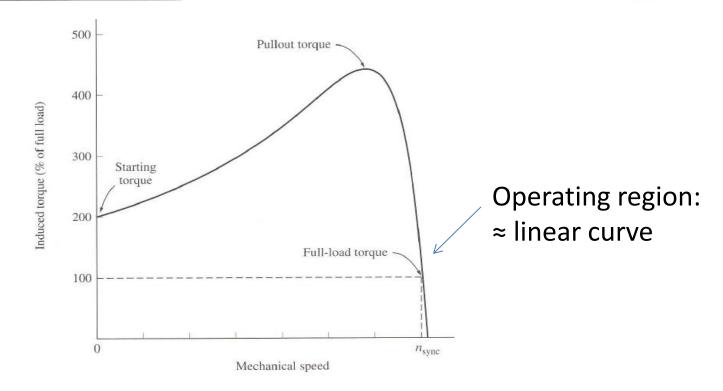


Torque-speed curve

$$\tau_{ind} = \frac{P_{AG}}{\omega_{sync}} = \frac{3V_{TH}^2 R_2 / S}{\omega_{sync} [(R_{TH} + R_2 / S)^2 + (X_{TH} + X_2)^2]}$$

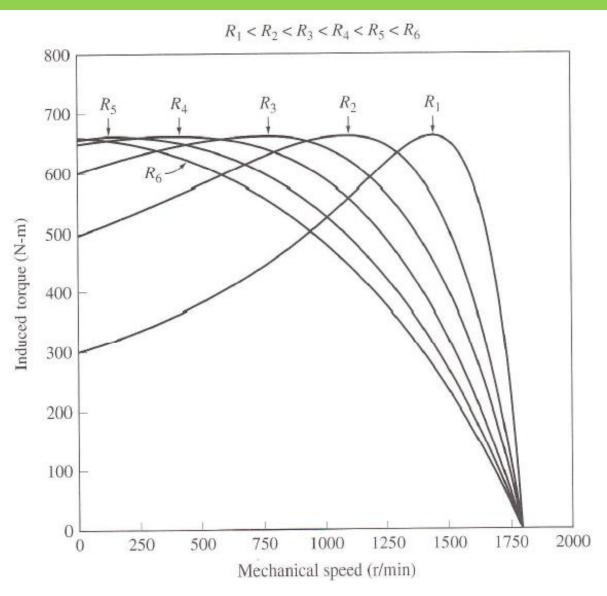
$$s_{\text{max}} = \frac{R_2}{\sqrt{R_{\text{TH}}^2 + (X_{\text{TH}} + X_2)^2}}$$

$$\tau_{\text{max}} = \frac{3V_{\text{TH}}^2}{2\omega_{\text{sync}}[R_{\text{TH}} + \sqrt{R_{\text{TH}}^2 + (X_{\text{TH}} + X_2)^2}]}$$

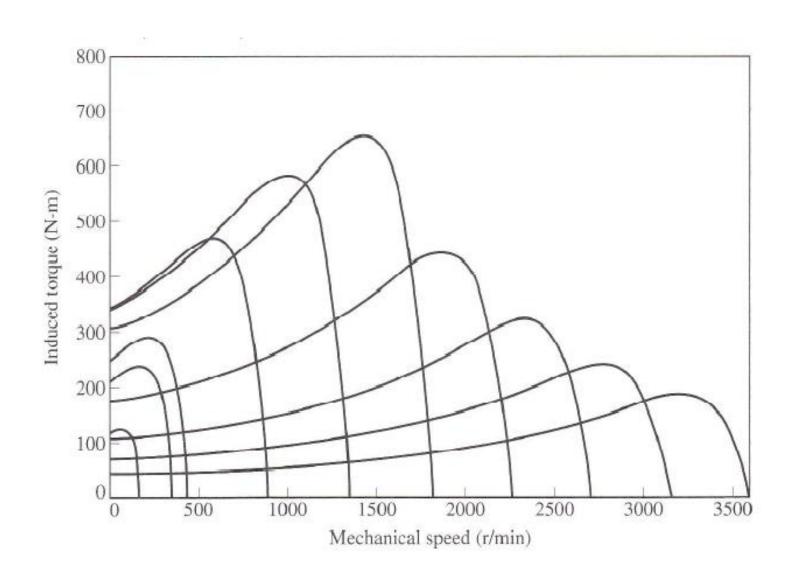


Effect of varying rotor resistance

(by adding external resistance to wound rotor)



Motor speed control by variable frequency (VFD)



Determining motor circuit parameters

Current-

• **DC Test** (or use Ohm-meter)

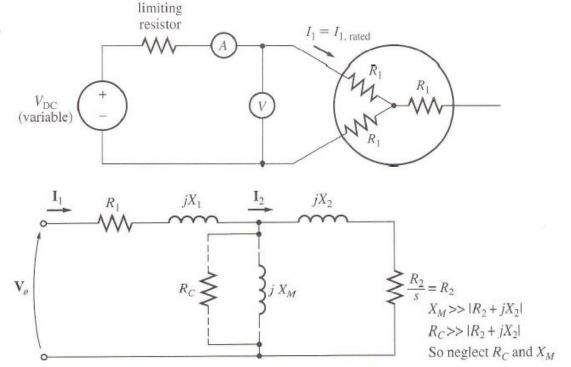
Measuring V, I \rightarrow R1

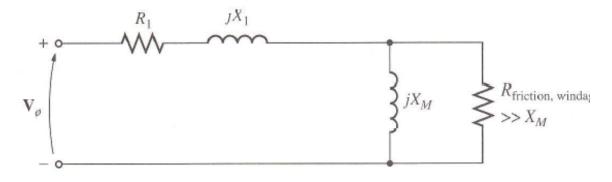


Measuring V_{ϕ} , I1, P, Q \rightarrow R1+R2, X1+X2

No-load Test

Measuring V ϕ , I1, P, Q \rightarrow R1, X1+Xm

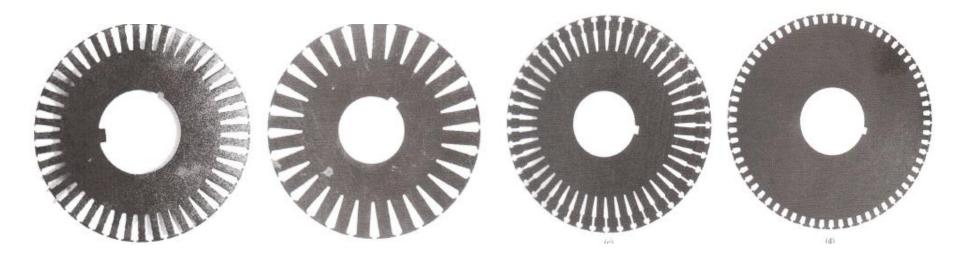




Rules of thumb for dividing stator and rotor leakage reactances

Cross section of squirrel cage rotor bars (NEMA Class A,B,C,D)

Rotor design	X_1 and X_2 as functions of X_{LR}	
	X ₁	X ₂
Wound rotor	0.5 <i>X</i> _{LR}	0.5X _{LR}
Design A	0.5 <i>X</i> _{LR}	0.5X _{LR}
Design B	0.4X _{LR}	0.6X _{LR}
Design C	0.3X _{LR}	0.7X _{LR}
Design D	0.5X _{LR}	0.5X _{LR}



Motor Specifications



Specifications: EFM4104T

208V AMPS:	76
BEARING-DRIVE-END:	6311
BEARING-OPP-DRIVE-END:	6309
CUSTOMER-PART-NUMBER:	
DESIGN CODE:	В
DOE-CODE:	010A
FL EFFICIENCY:	93.6
ENCLOSURE:	TEFC
FRAME:	286T
GREASE:	POLYREX EM
HERTZ:	60
CATALOG NUMBER:	EFM4104T
SPEC. NUMBER:	10C156Y758G1
INSULATION-CLASS:	F
KVA-CODE:	G
MAX. SPACE HEATER TEMP.:	
SPEED [rpm]:	1770
OUTPUT [hp]:	30
PHASE:	3
POWER-FACTOR:	83
RATING:	40C AMB-CONT
SERIAL-NUMBER:	
SERVICE FACTOR:	1.15
SPACE-HEATER-AMPS:	
SPACE-HEATER-VOLTS:	
VOLTAGE:	230/460
FL AMPS:	72/36

Problems

- 7.4
- 7.5
- 7.7*, 7.8, 7.10
- 7.14, 7.15
- 7.18
- 7.19