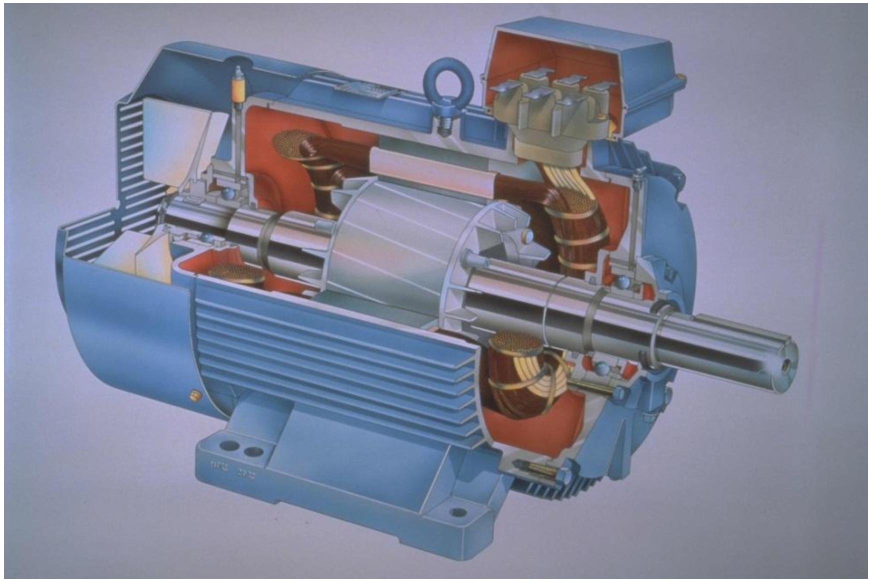


Induction Machines

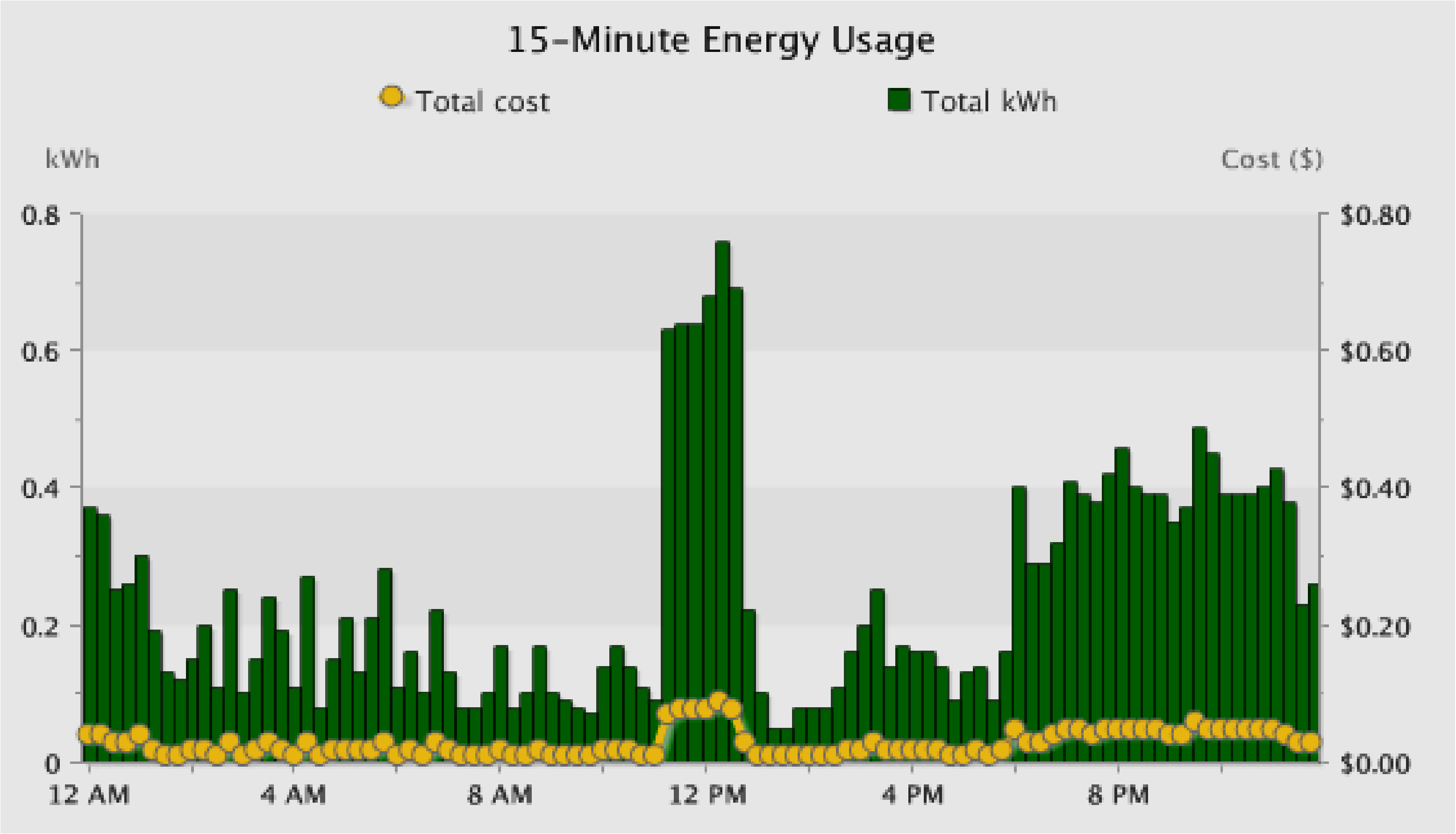
EE 340

Spring 2012

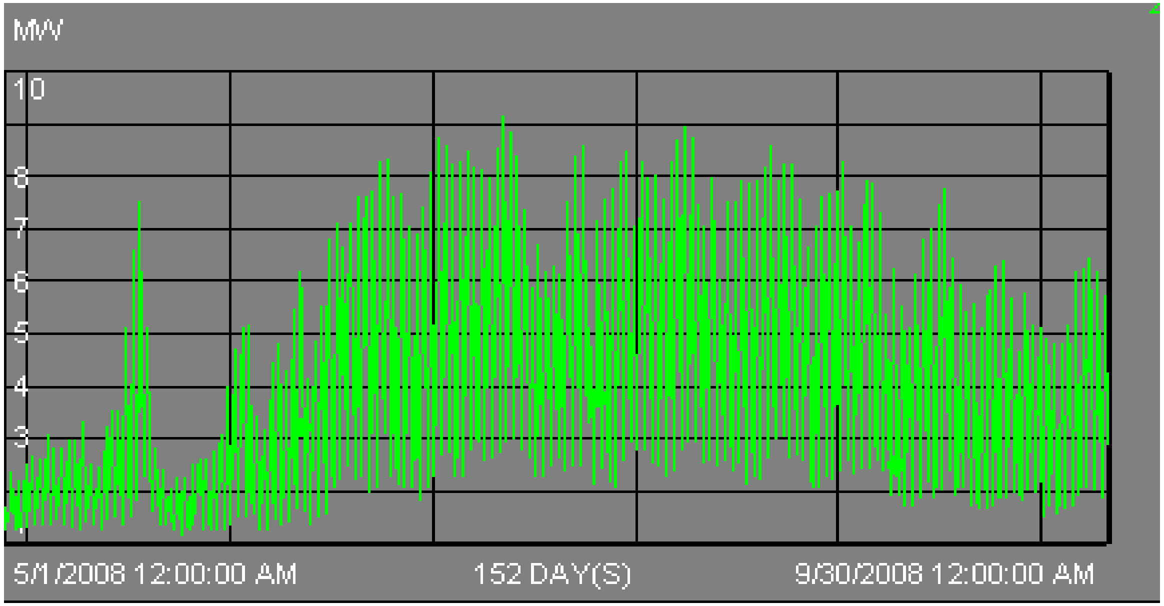
Where does the power go?

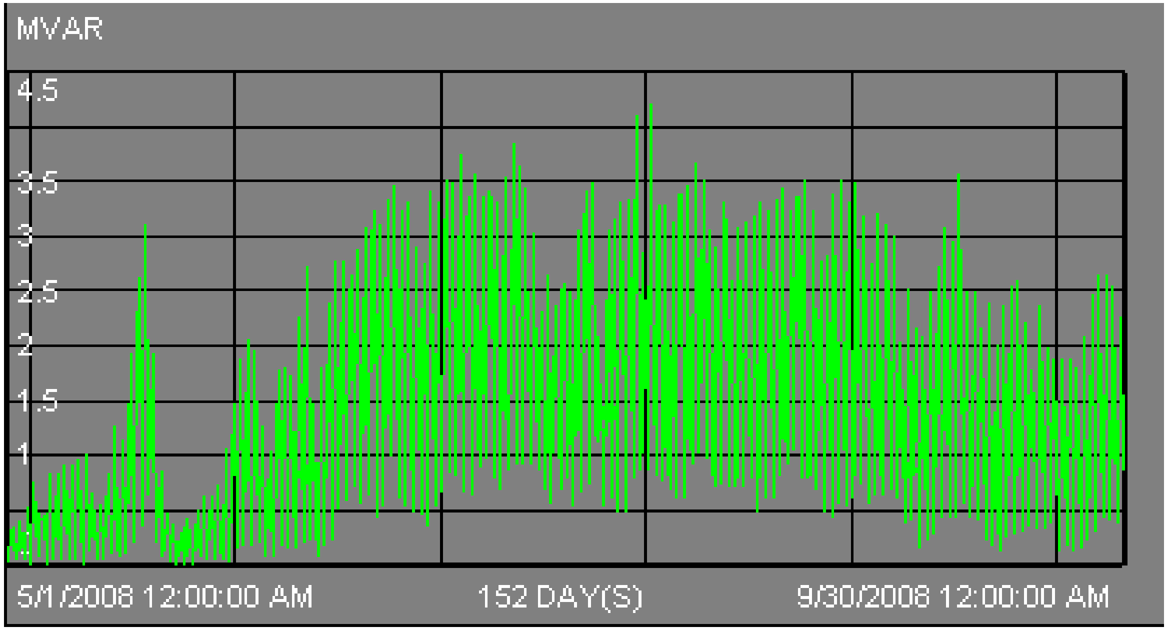
- The electric energy generated purchased by consumers for different needs. This energy is converted to different forms:
  - Lighting (indoor/outdoor – CFL, incandescent, LED, Halogen…)
  - Heating (electric water heaters, clothes dryers, electric stoves and ovens)
  - Conversion to mechanical power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

Power Demand – Individual Customer

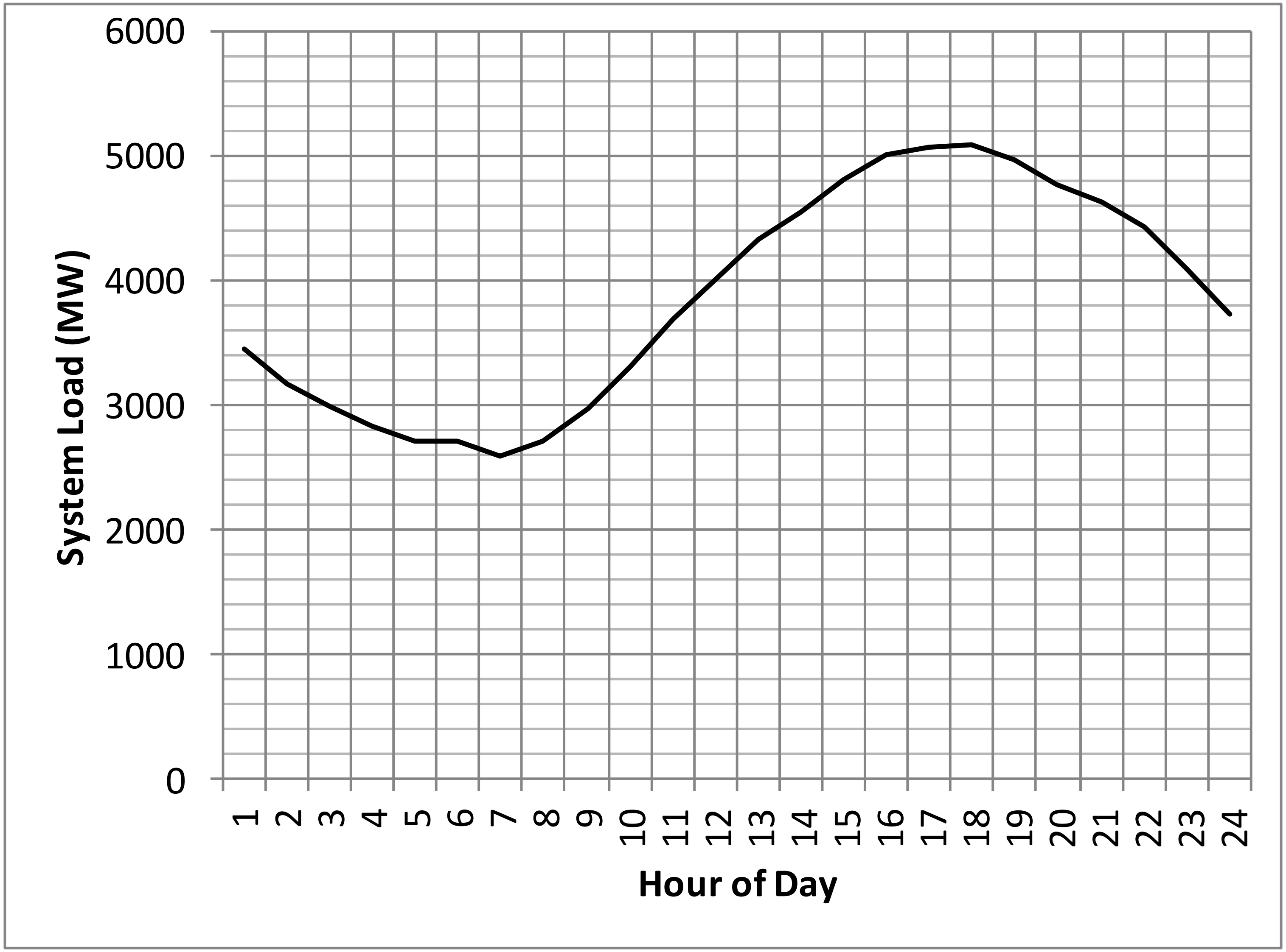


MW and MVAR loading on a feeder

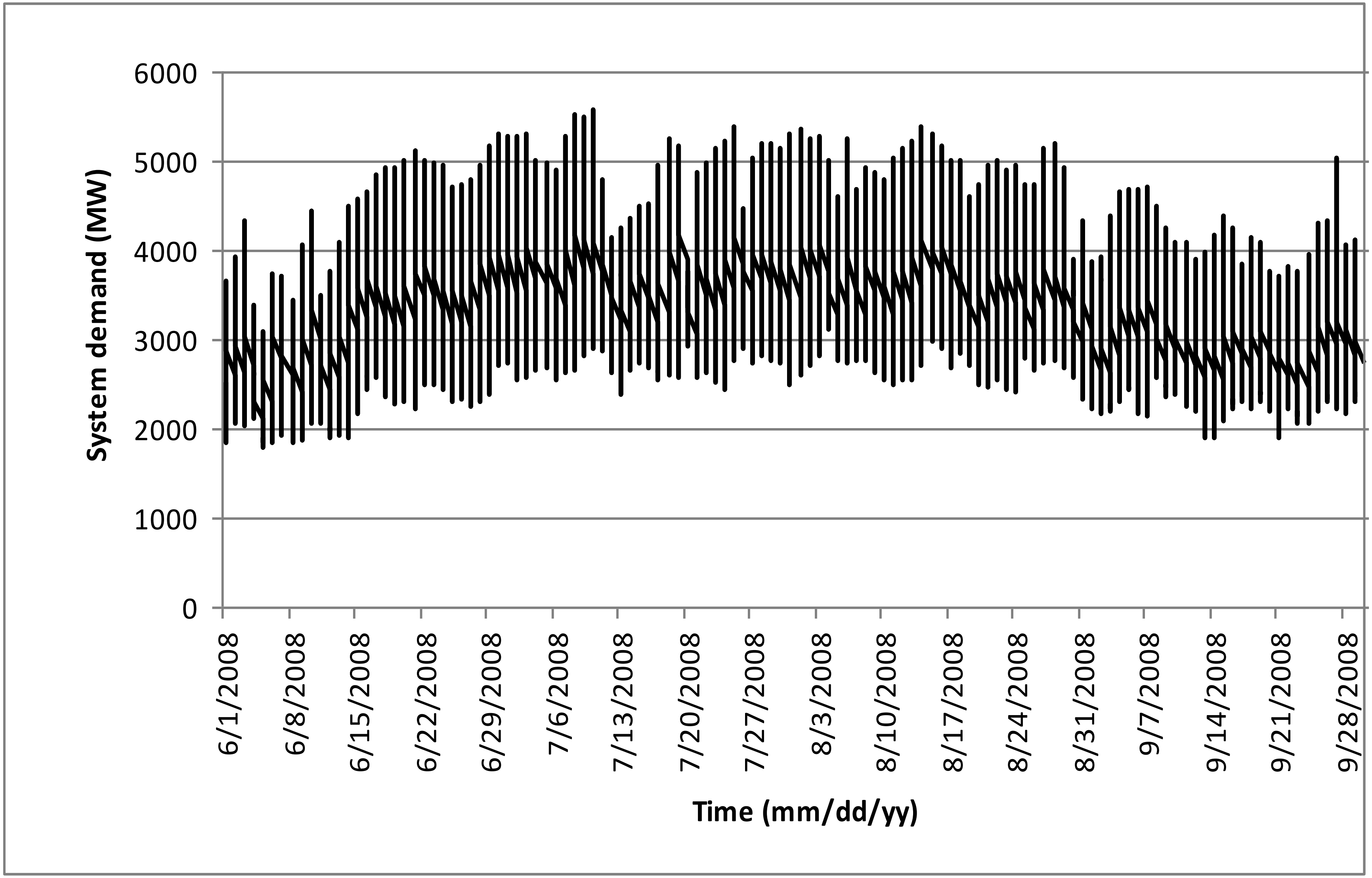




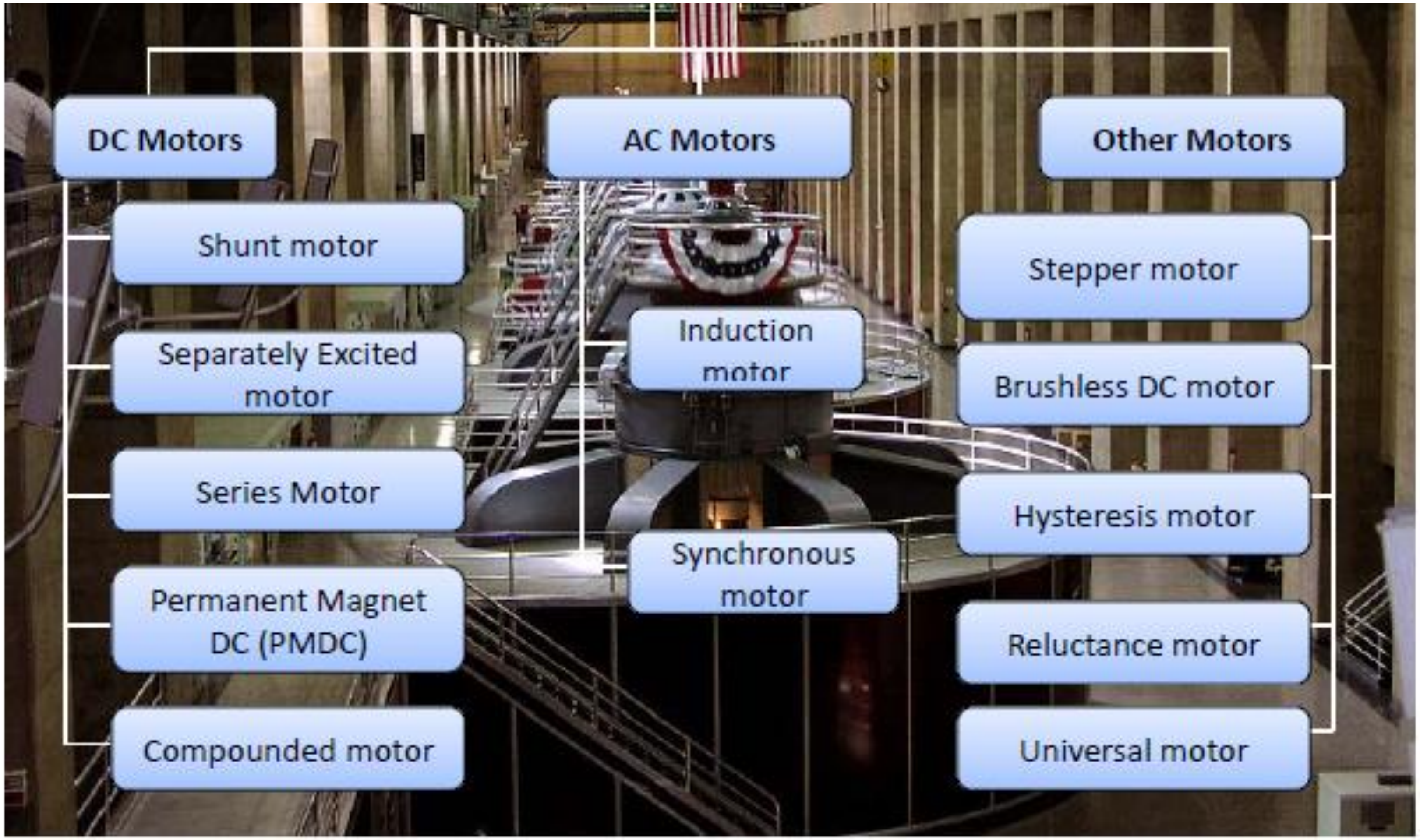
System load: 24-hours



System load: 4-month period

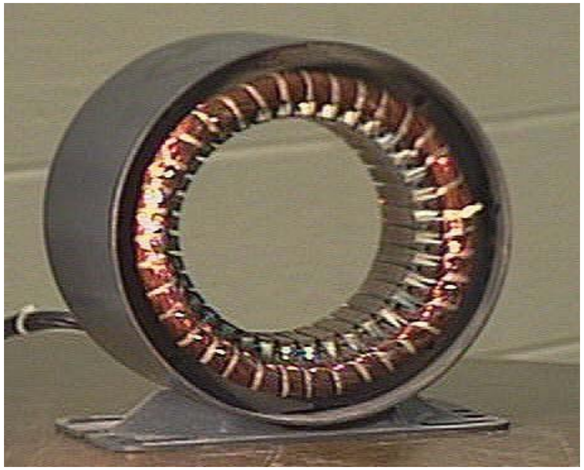


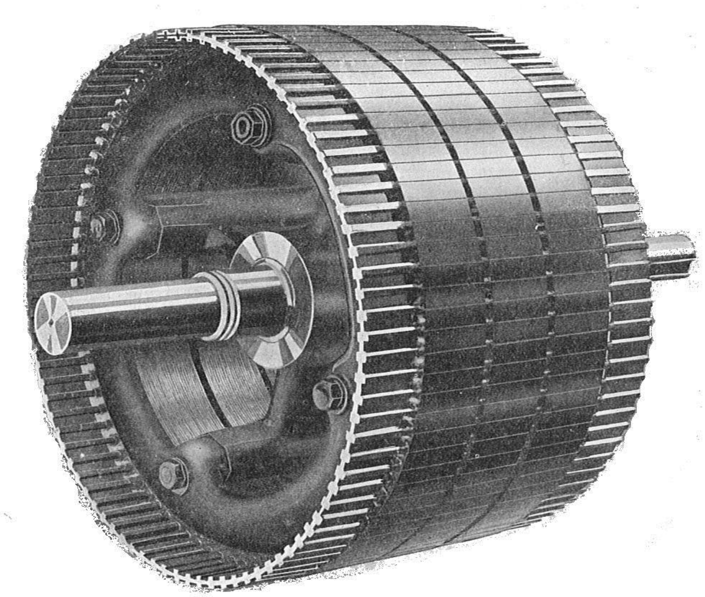
Types of Electric Motors



3-Phase induction machine construction

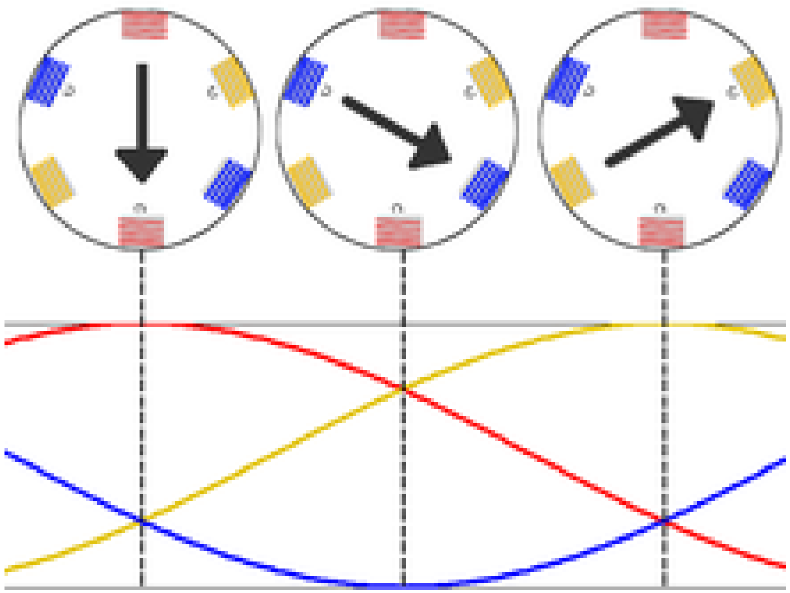
- 3 stator windings (uniformly distributed as in a synchronous generator)
- Two types of rotor:
  - Squirrel cage
  - Wound rotor (with slip rings)





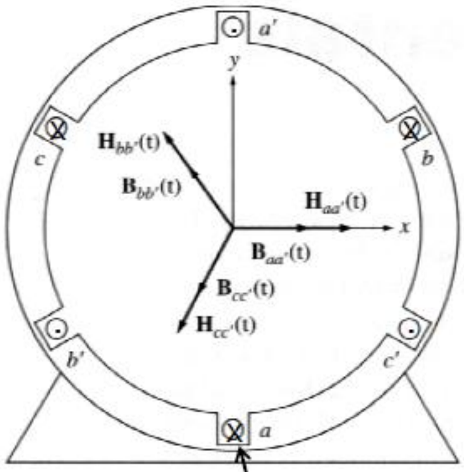
The rotating magnetic field

- 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 the stator field.
- The 3-phase set of currents, each of equal magnitude and with a phase difference of 120^o, flow in the stator windings and generate a rotating field will constant magnitude.



The rotating magnetic field

- Consider a simple 3-phase stator containing three coils, each 120° apart. Such a winding will produce only one north and one south magnetic pole; therefore, this motor would be called a two pole motor.
- Assume that the currents in three coils are:



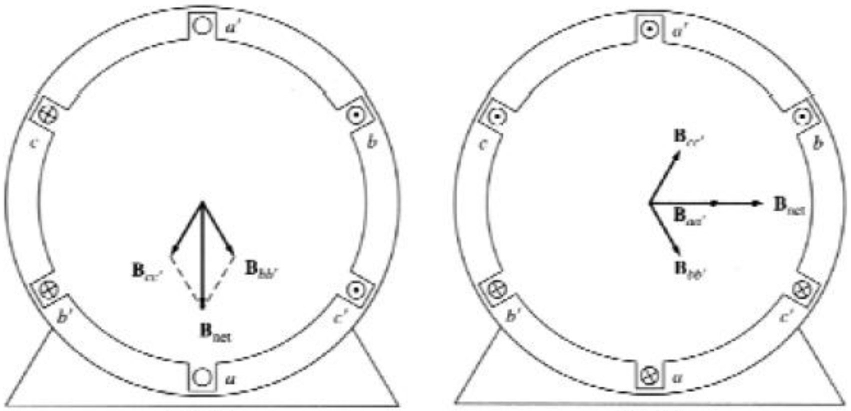
$$\begin{cases} i_{aa'}(t) = I_M \sin \omega t \\ i_{bb'}(t) = I_M \sin\left(\omega t - 120^0\right) \\ i_{cc'}(t) = I_M \sin\left(\omega t - 240^0\right) \end{cases}$$

- The magnetic flux density in the stator at any arbitrary moment is given by

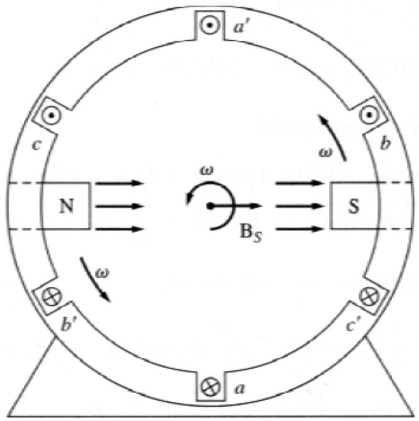
$$B_{net}(t) = B_{aa'}(t) + B_{bb'}(t) + B_{cc'}(t)$$

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 as a north pole and a south pole.



$\omega t = 0°$ $\omega t = 90°$



- For a two pole machine,

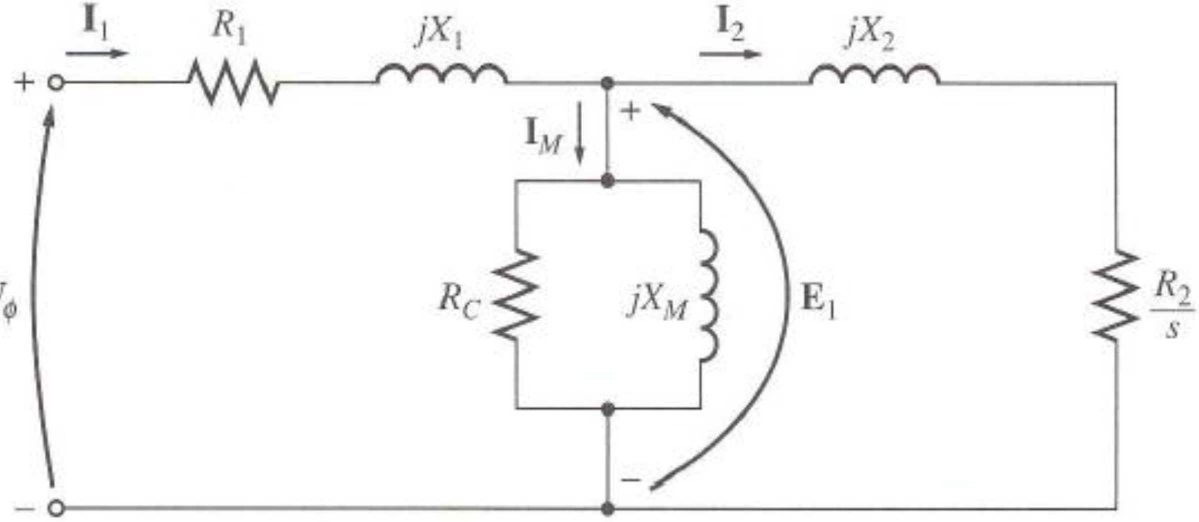
$$f_e\,(Hz) = f_m\,(rps) = \frac{1}{60} n_s\,(rpm)$$

- For a p-pole machine,

$$f_e\,(Hz) = \frac{p}{2} f_m\,(rps) = \frac{p}{120} n_s\,(rpm)$$

Per-phase equivalent circuit

- Motor Slip $$s = \frac{n_s - n_m}{n_s}$$
- R_1 and R_2: stator and rotor winding resistances
- X_1 and X_2: 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

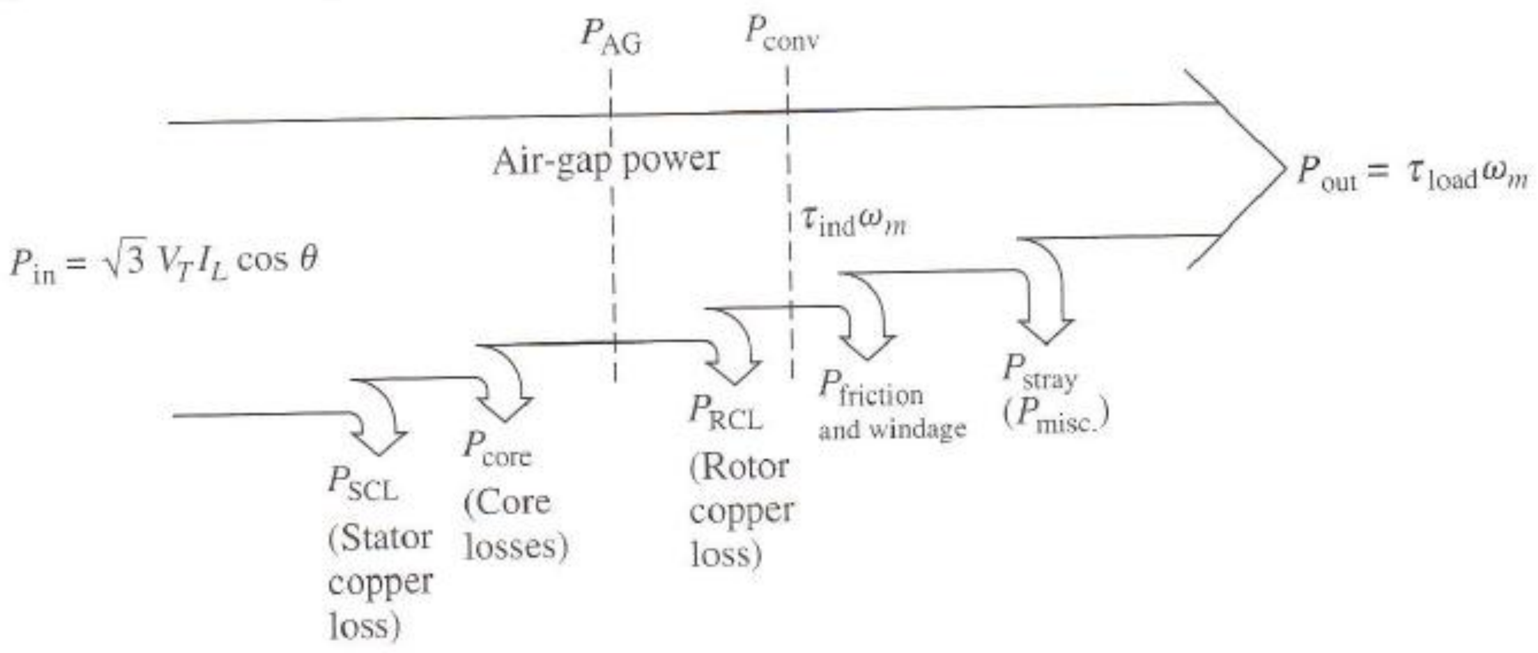
$$P_{SCL} = 3I_1^2 R_1$$

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

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

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

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



Simplified per-phase equivalent circuit

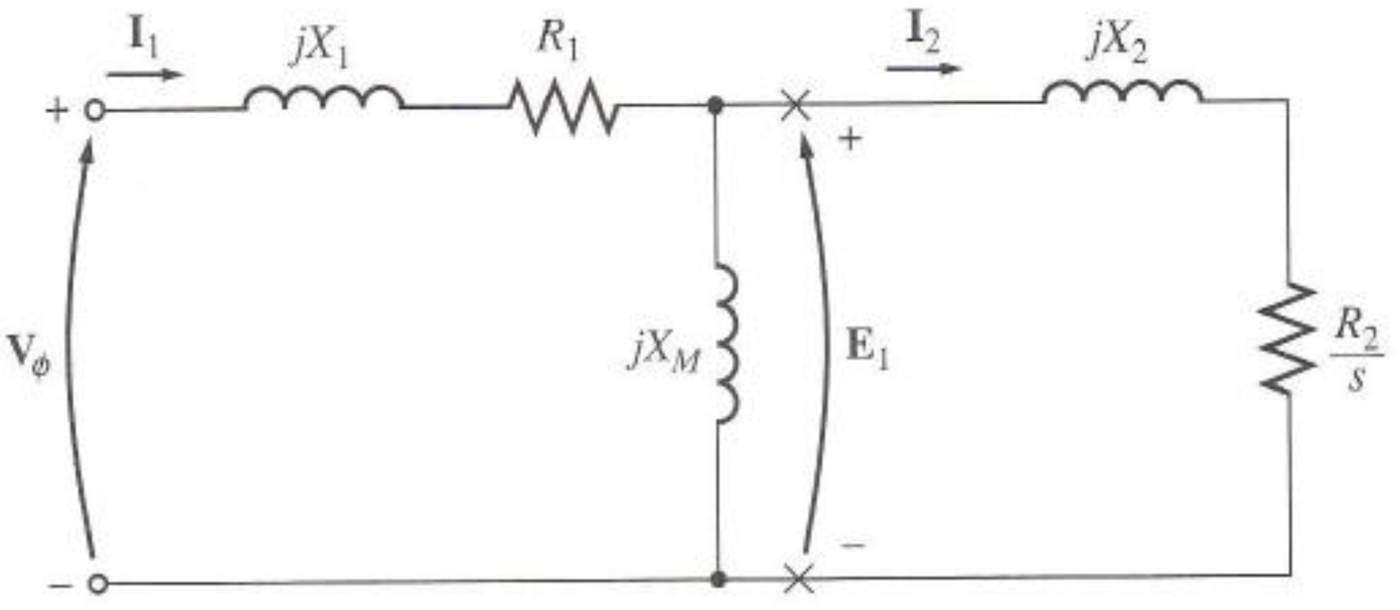
- Core loss is embedded with friction, windage and stray-load loss

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

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

$$P_{AG} = 3I_2^2 (R_2 / S) = \tau_{ind}\omega_{sync}$$

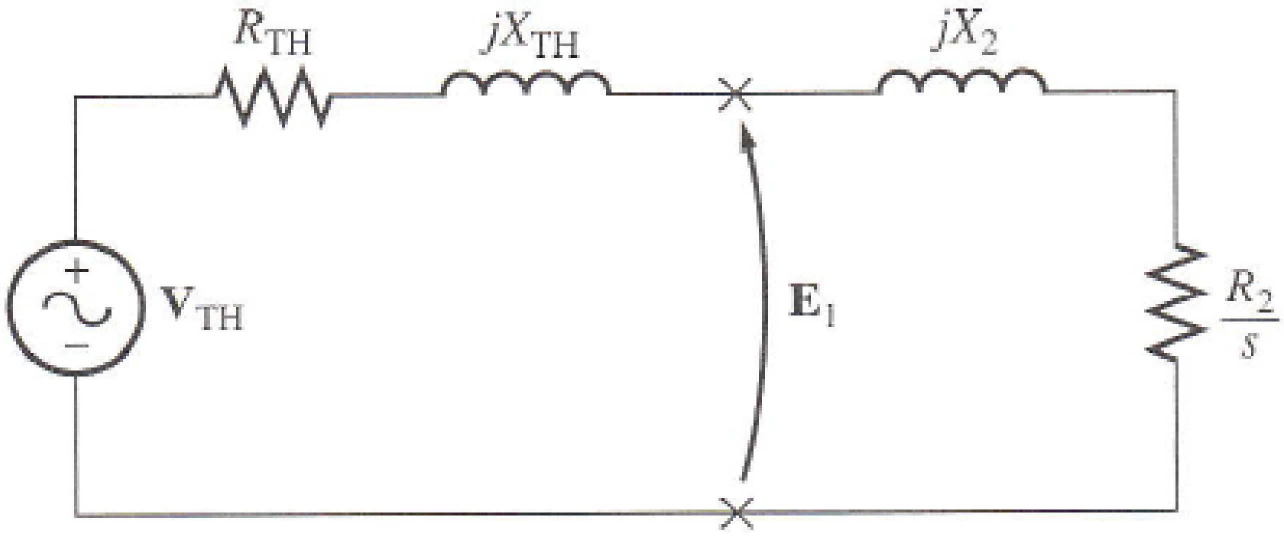
$$P_{conv} = P_{AG} - P_{RCL} = 3I_2^2 R_2 (1 - S) / S = \tau_{ind}\omega_m$$



Thevenin equivalent circuit and torque-slip equation

$$V_{TH} \approx V_{\phi} \frac{X_M}{X_1 + X_M}, \; X_{TH} \approx X_1, \; R_{TH} \approx R_1 \left(\frac{X_M}{X_1 + X_M}\right)^2$$

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

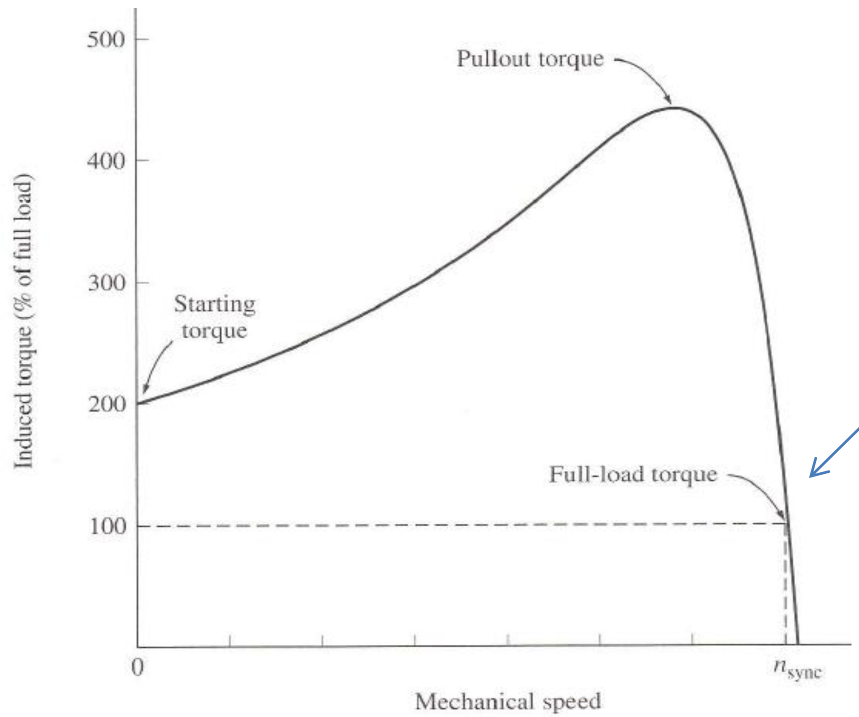


Torque-speed curve

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

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

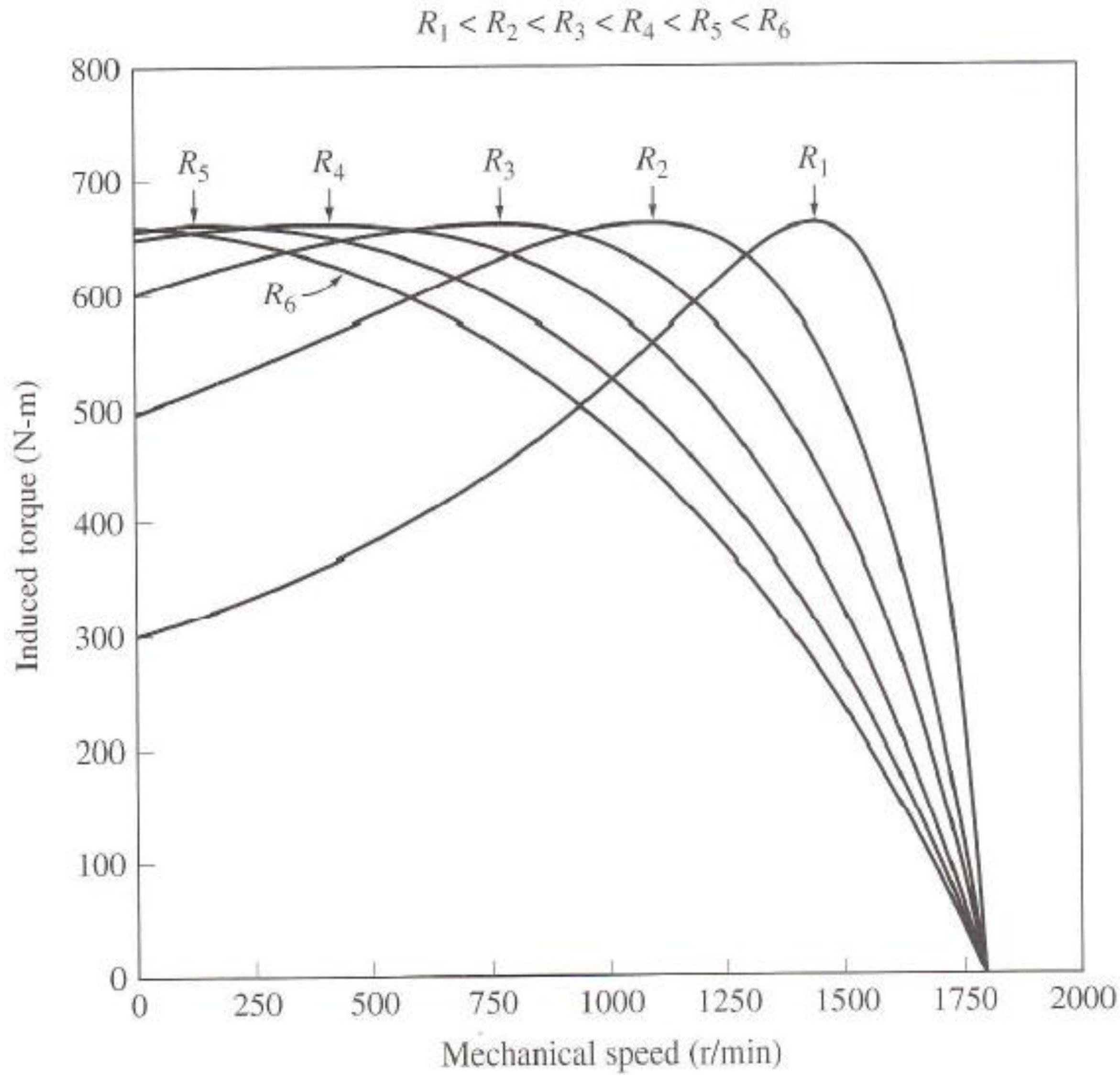
$$\tau_{max} = \frac{3V_{TH}^2}{2\omega_{sync}\left[R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}\right]}$$



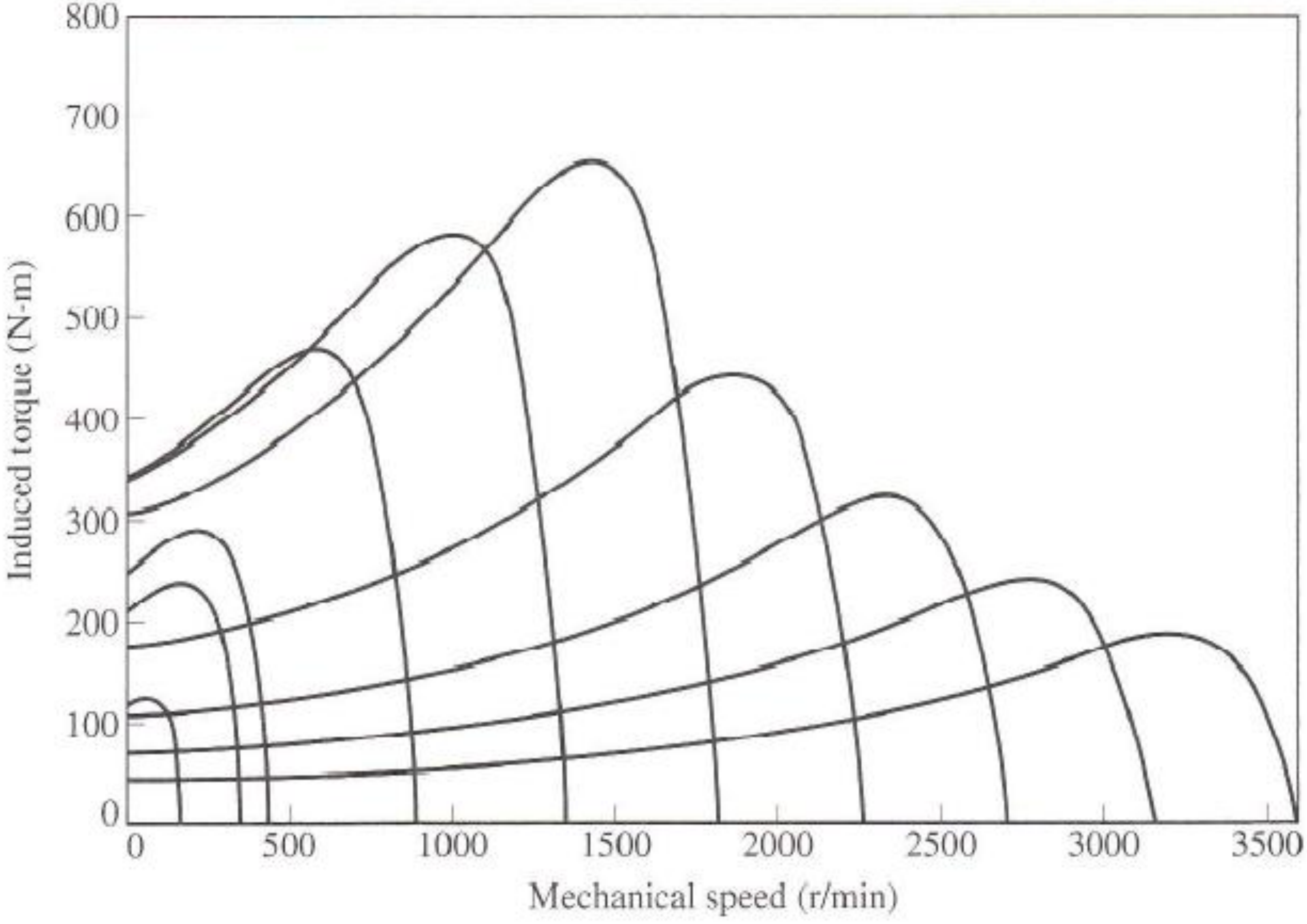
Operating region:
≈ linear curve

Effect of varying rotor resistance

(by adding external resistance to wound rotor)



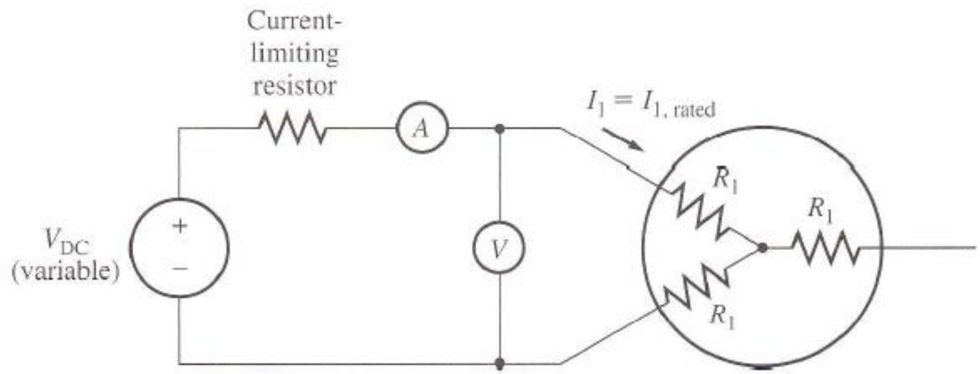
Motor speed control by variable frequency (VFD)



Determining motor circuit parameters

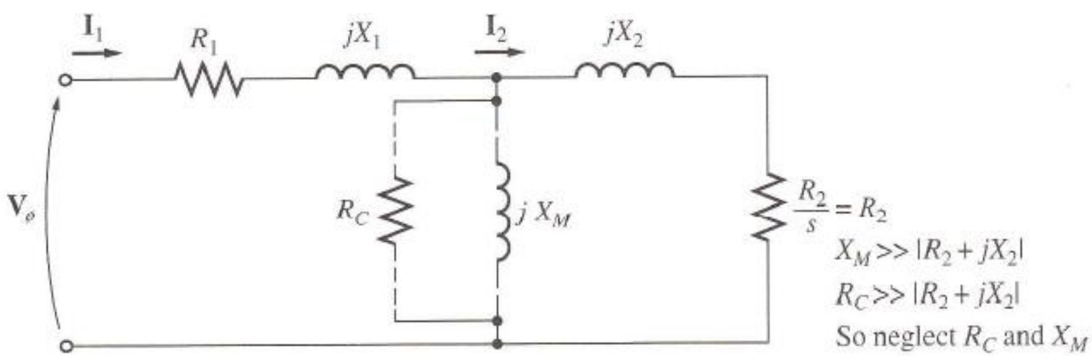
- **DC Test**

  Measuring V, I → R1



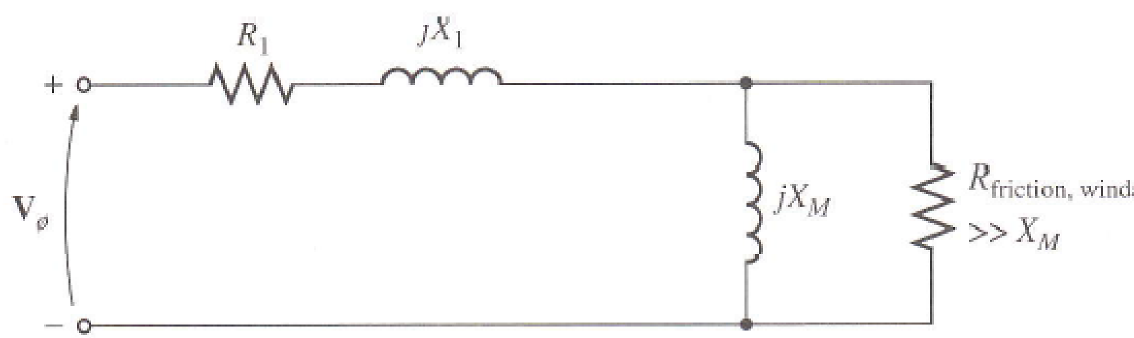
- **Locked-rotor Test**

  Measuring Vϕ, I1, P, Q → R1+R2, X1+X2



- **No-load Test**

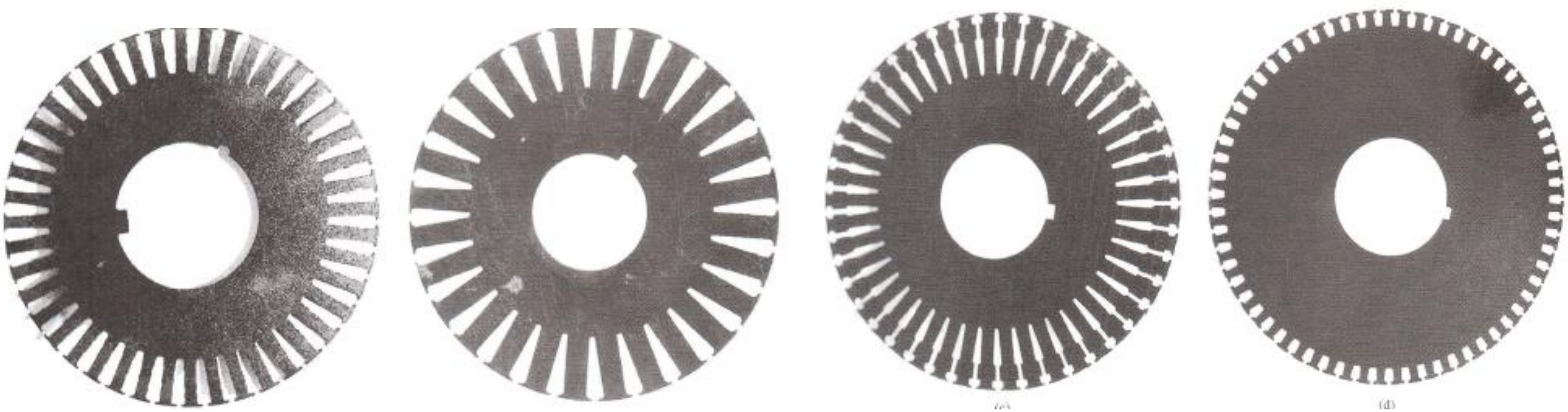
  Measuring Vϕ, I1, P, Q → R1, X1+Xm



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	$0.5X_{LR}$	$0.5X_{LR}$
Design A	$0.5X_{LR}$	$0.5X_{LR}$
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:	B
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