Lecture 2

EE3010: Electrical Devices and Machines

School of Electrical and Electronic Engineering

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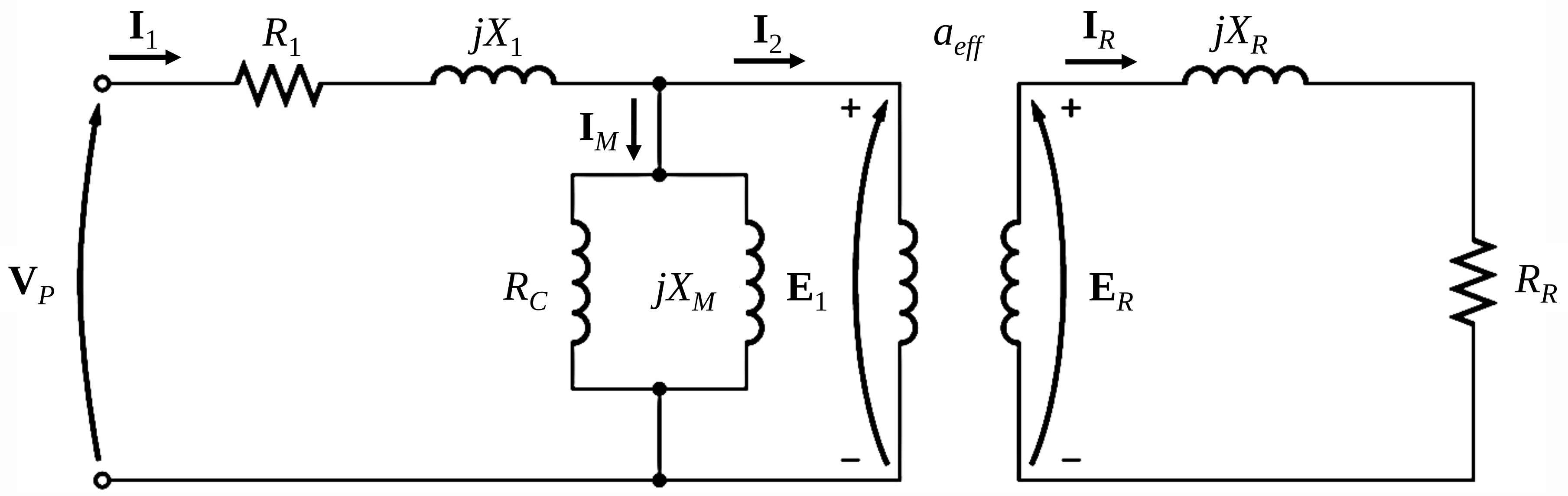
Learning Objectives

By the end of this lecture, you should be able to:

- Describe the equivalent circuit of an induction motor.
- Describe the power flows and power flow diagram of an induction motor.
- Calculate the various powers and motor efficiency of an induction motor from given power losses and operating conditions.

The Equivalent Circuit of an Induction Motor

- Because the induction of voltages and currents in the rotor circuit of an induction motor is essentially a transformer action, the equivalent circuit of an induction motor is very similar to that of a transformer.



Per phase equivalent circuit of an induction motor, with rotor and stator connected by an ideal transformer of turns ratio a_{eff}.

The Equivalent Circuit of an Induction Motor

- The circuit parameters per phase:
  - R_1 : Stator winding resistance
  - X_1 : Stator leakage reactance
  - R_R : Rotor winding resistance
  - X_R : Rotor leakage reactance
  - a_{eff} : Effective turns ratio coupling E_1 and E_R
  - R_C : Resistance representing core loss
  - X_M : Magnetising reactance

The Rotor Circuit Model

- In an induction motor, when a voltage is applied to the stator windings, a voltage is induced in the rotor windings.
- The induced voltage is 0 V when the rotor moves at synchronous speed.
- When the rotor is stationary (i.e. locked-rotor or blocked-rotor conditions), the largest voltage and rotor frequency are induced in rotor.

The Rotor Circuit Model

❖ At any other speed,

- The rms value of the induced voltage generated in the rotor as it is swept by the rotating flux is

$$E_R = 4.44(f_r)N_r\phi_{\max} = 4.44(sf_s)N_r\phi_{\max} = sE_{RO}$$

where $E_{RO} = 4.44(f_s)N_r\phi_{\max}$ is the rotor induced voltage at locked-rotor conditions ($f_r = f_s,\ s = 1$).

- The reactance depends on the inductance and the frequency of the voltage and current in the rotor.

$$X_R = \omega_r L_R = 2\pi(f_r)L_R = 2\pi(sf_s)L_R = sX_{RO}$$

where X_{RO} is the blocked-rotor reactance.

Example 1

The frequency and induced voltage in the rotor of a certain six-pole wound-rotor induction motor, whose shaft is blocked, are 60 Hz and 100 V, respectively. Determine the corresponding values when the rotor is running at 1100 r/min.

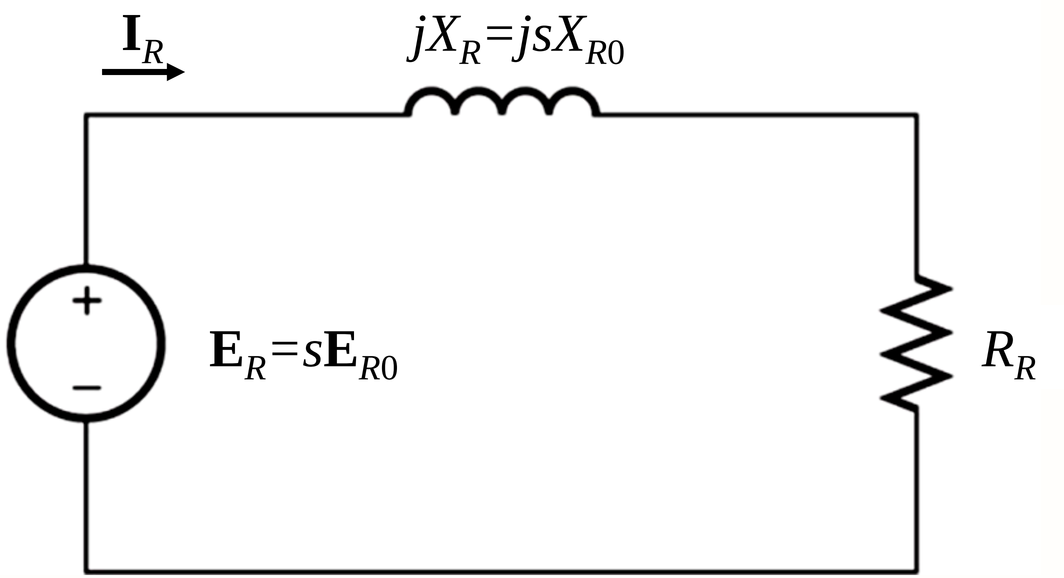
$$n_{sync} = \frac{120 f_s}{p} = \frac{120(60)}{6} = 1200 \text{ r/min}$$

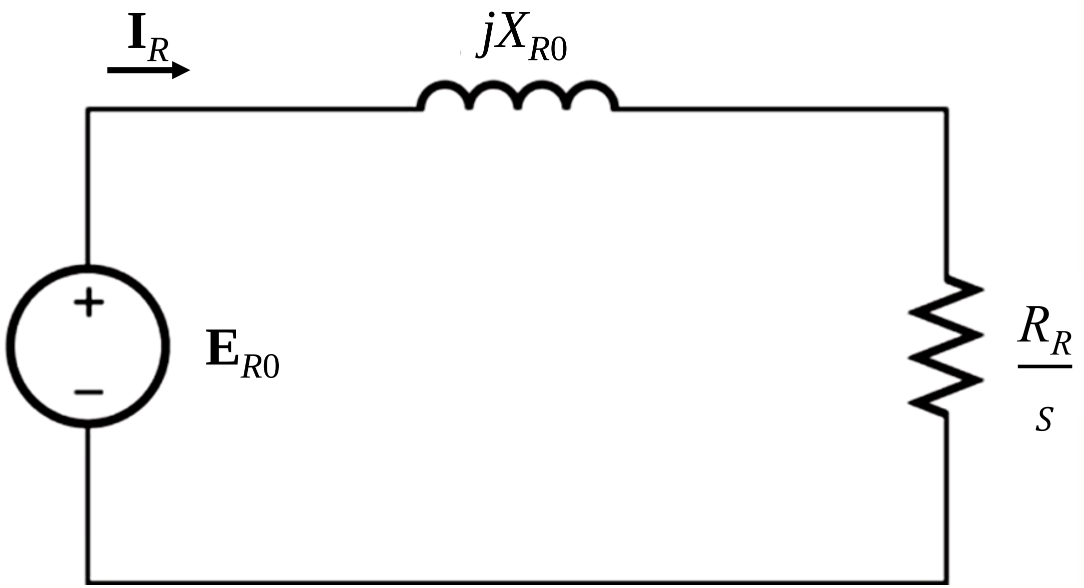
$$s = \frac{n_{sync} - n_m}{n_{sync}} = 0.0833$$

$$f_r = s f_s = 5 \text{ Hz}$$

$$E_R = s E_{RO} = 8.33 \text{ V}$$

The Rotor Circuit Model





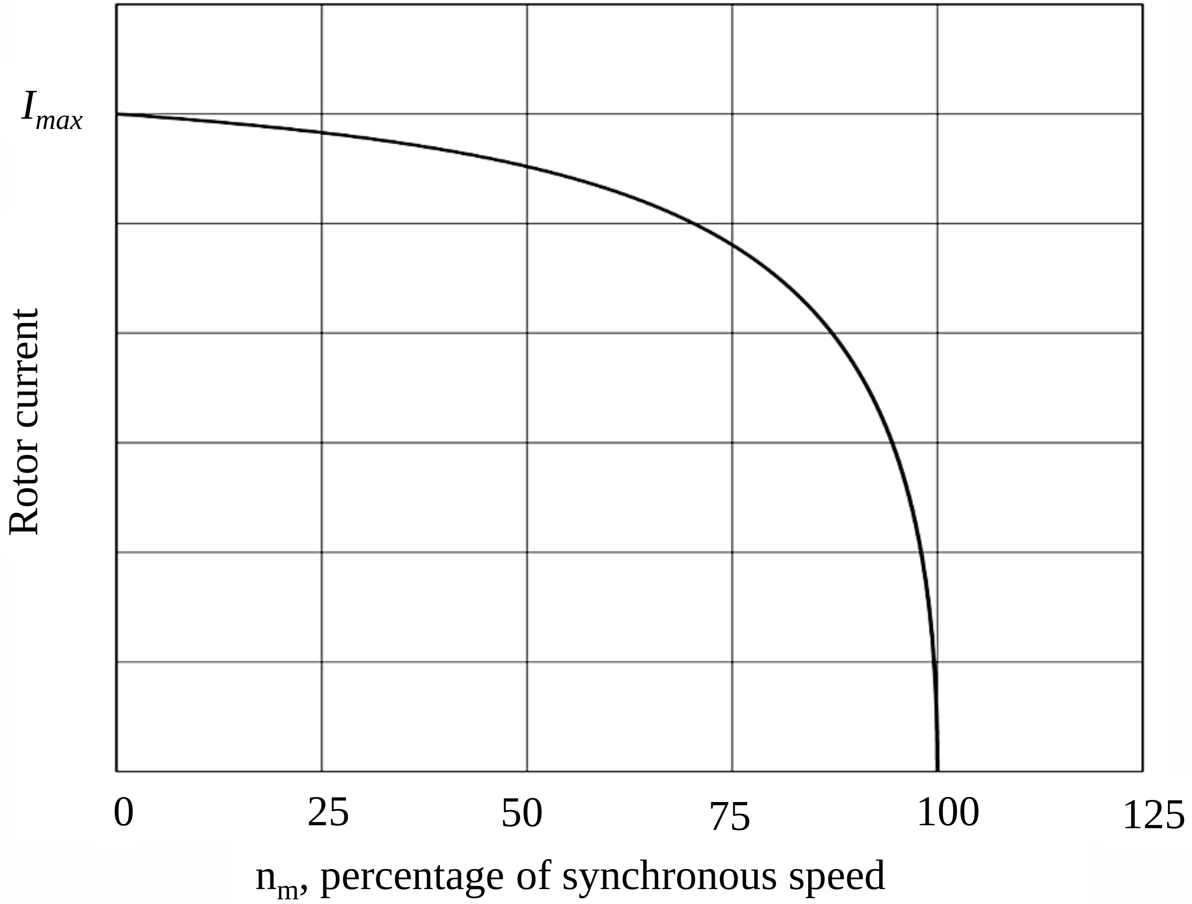
The rotor circuit model of an induction motor.

The rotor circuit model with all the frequency (slip) effects concentrated in resistor $\frac{R_R}{s}$.

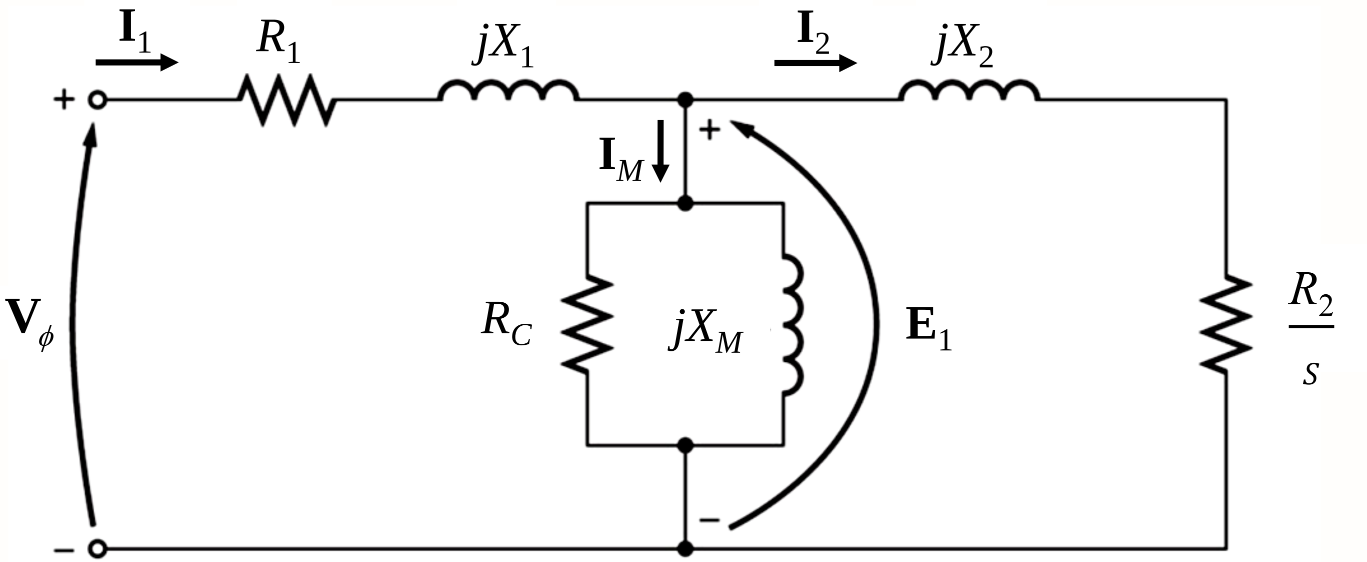
The Rotor Circuit Model

❖ Rotor current as a function of rotor speed

$$\mathbf{I}_R = \frac{\mathbf{E}_{RO}}{R_R/s + jX_{RO}}$$



The Final Equivalent Circuit of an Induction Motor



The per phase equivalent circuit of an induction motor referred to the stator.

- ❖ The core losses (W) are usually lumped together with friction, windage and stray losses and called the rotational losses.
- ❖ Hence, unless specified otherwise, R_C will not appear in the equivalent circuit subsequently.

The Final Equivalent Circuit of an Induction Motor

❖ The referred rotor parameters to the stator side are:

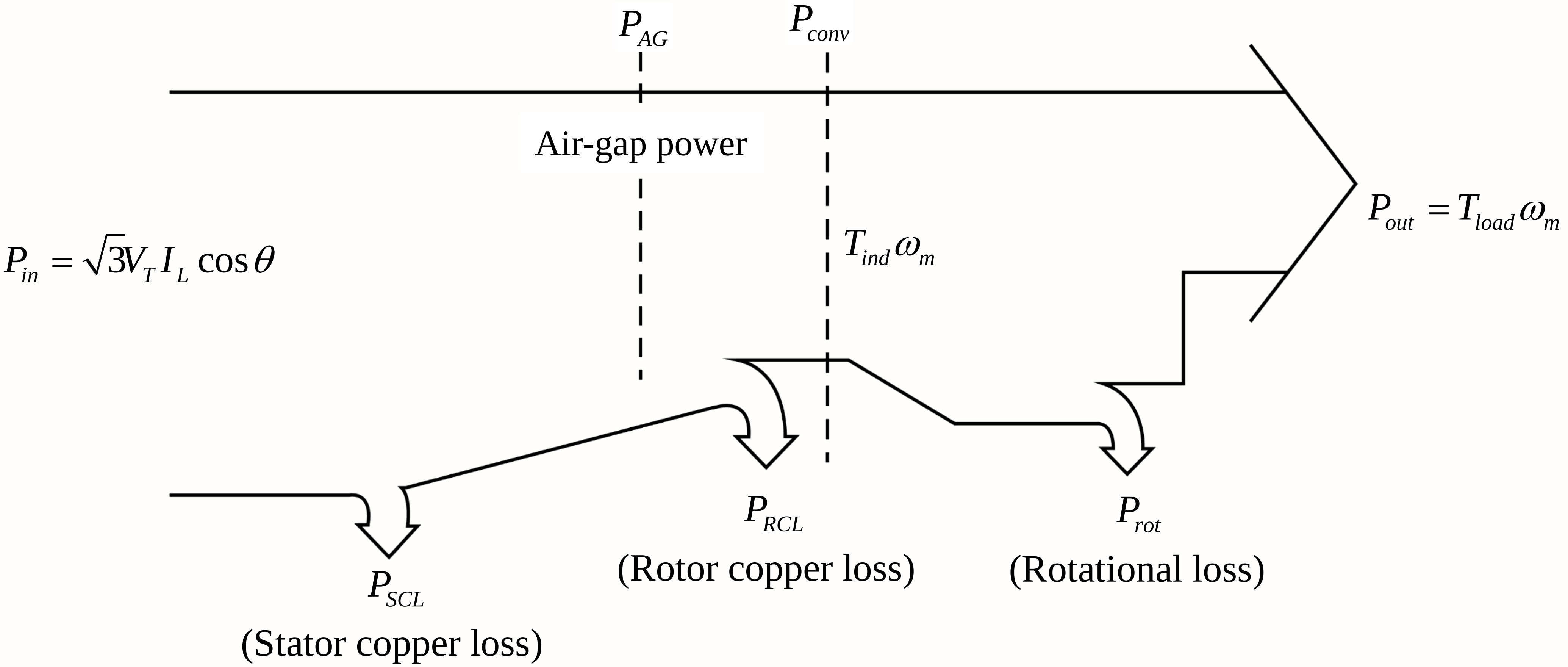
$$\mathbf{E}_1 = a_{eff}\mathbf{E}_{RO} \ ,$$

$$\mathbf{I}_2 = \frac{\mathbf{I}_R}{a_{eff}} \text{ where } \mathbf{I}_R = \frac{\mathbf{E}_{RO}}{R_R/s + jX_{RO}}$$

$$R_2 = a_{eff}^2 R_R \ , \qquad X_2 = a_{eff}^2 X_{RO}$$

$$a_{eff} = \text{effective turns ratio}$$

Losses and Power-Flow Diagram in Induction Motors



Power flow diagram of an induction motor.

Losses and Power-Flow Diagram in Induction Motors

- Induction motor basically is a rotating transformer.
- Input is 3-phase supply.
- Output is mechanical power.
- Air gap power is the power transferred to the rotor of the machine across the air gap between the stator and the rotor.
- The converted power is the power converted from electrical to mechanical form.
- The core losses are usually <u>lumped together with the friction, windage and stray load losses and called the rotational losses</u>.

Example 2

A 480 V, 60 Hz, 50-hp, three-phase induction motor is drawing 60 A at 0.85 pf lagging. The stator copper losses are 2 kW, and the rotor copper losses are 700 W. The total rotational losses which includes the friction, windage and core losses are 2400 W, and the stray losses are negligible. Find:

a) The air-gap power P_{AG}

b) The converted power P_{conv}

c) The output power P_{out}

d) The efficiency of the motor η

(Solutions →)

Example 2 – Solutions

a) $$P_{\text{in}} = \sqrt{3} V_{line} I_{line} \cos\theta$$

$$= \sqrt{3}(480)(60)0.85 = 42.4 \text{ kW}$$

$$P_{AG} = P_{in} - P_{SCL} = 40.4 \text{ kW}$$

b) $$P_{conv} = P_{AG} - P_{RCL} = 39700 \text{ W}$$

c) $$P_{out} = P_{conv} - P_{rot} = 37.3 \text{ kW}$$

d) The efficiency of the motor $\eta = \dfrac{P_{out}}{P_{in}}(100\%) = 88\%$

Summary

In this lecture, you have learnt:

- ❖ The equivalent circuit of an induction motor turns out to be very similar to the equivalent circuit of a transformer.

- ❖ The power flow diagram of an induction motor.

- ❖ The computations of the various powers and motor efficiency of an induction motor from given power losses and operating conditions.

References

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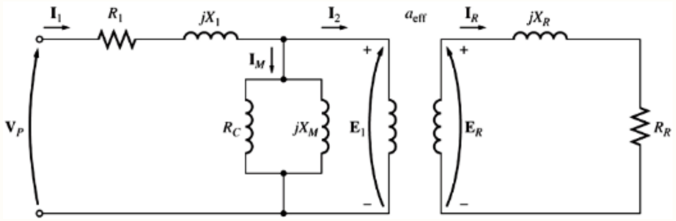
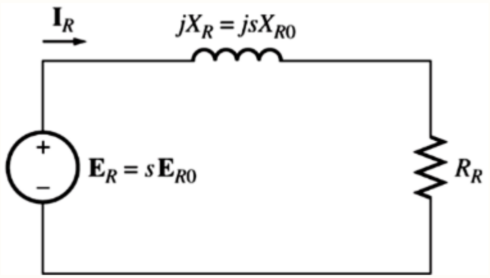
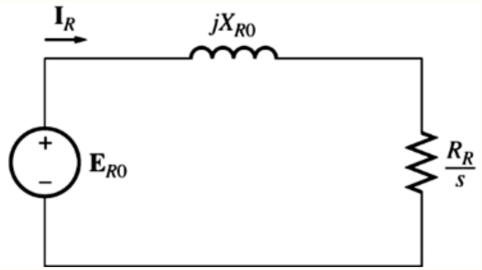
1	3		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 318), by S. J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
2	8		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 318), by S. J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
3	8		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 319), by S. J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.

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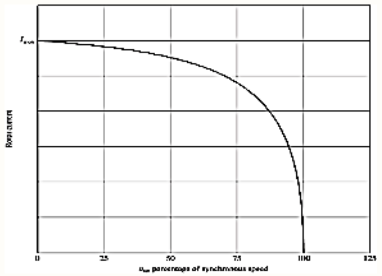
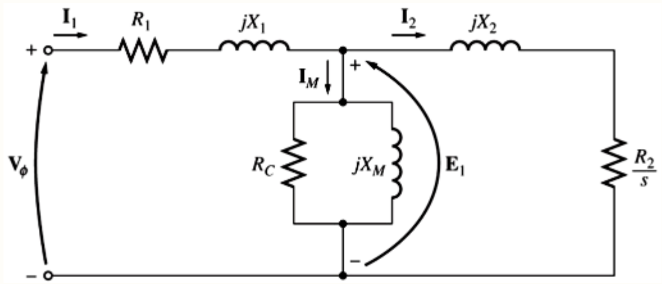
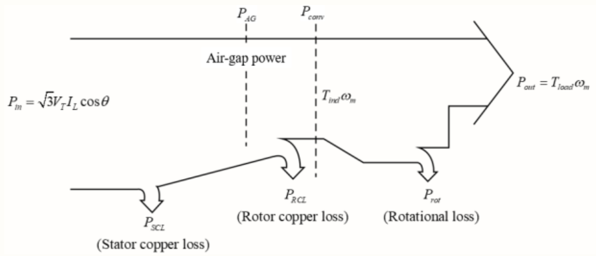
4	9		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 319), by S. J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
5	10		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 321), by S. J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
6	12		Adapted from *Electric Machinery Fundamentals, 5th ed.*, (p. 322), by S. J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Adapted with permission.