Chapter 11

ELECTRIC MOTOR DRIVES

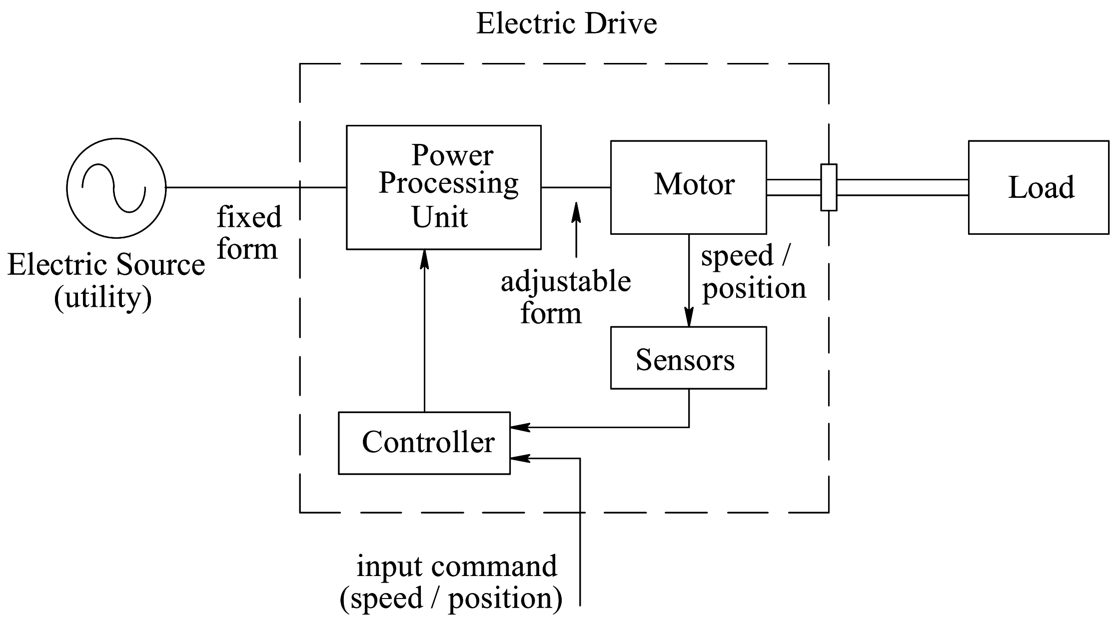


Figure 11-1 Block diagram of an electric drive system.

MECHANICAL SYSTEM REQUIREMENTS

Rotational Motor-Load Systems:

$$\underset{[Nm]}{T} = \underset{[N]}{f}\ \underset{[m]}{r}$$

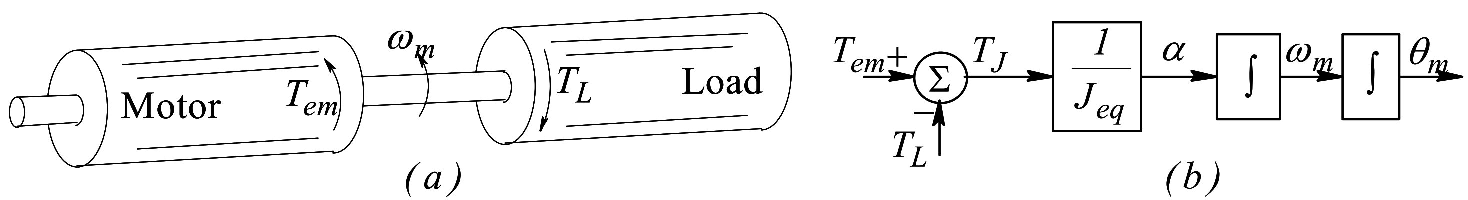


Figure 11-2 Motor and load torque interaction with a rigid coupling.

$$\alpha = \frac{T_J}{J_{eq}} \qquad \omega_m(t) = \omega_m(0) + \int_0^t \alpha(\tau)d\tau \qquad \theta_m(t) = \theta_m(0) + \int_0^t \omega_m(\tau)d\tau$$

Power and Energy in Rotational Systems

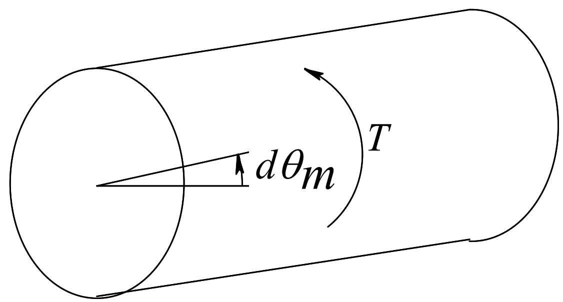


Figure 11-3 Torque, work and power.

$$dW = T\,d\theta_m$$

$$p = \frac{dW}{dt} = T\frac{d\theta_m}{dt} = T\omega_m$$

Electrical Analogy

Table 11-1 Torque–Current Analogy

Mechanical System	Electrical System
Torque (T)	Current (i)
Angular speed (ω_m)	Voltage (v)
Angular displacement (θ_m)	Flux linkage (ψ)
Moment of inertia (J)	Capacitance (C)

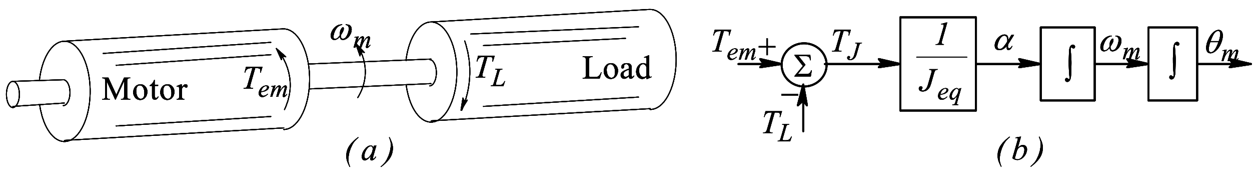


Figure 11-2 Motor and load torque interaction with a rigid coupling.

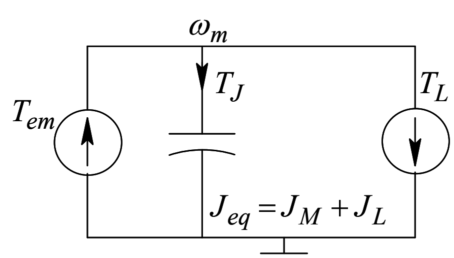


Figure 11-4 Electrical Analogy.

INTRODUCTION TO ELECTRIC MACHINES AND THE BASIC PRINCIPLES OF OPERATION

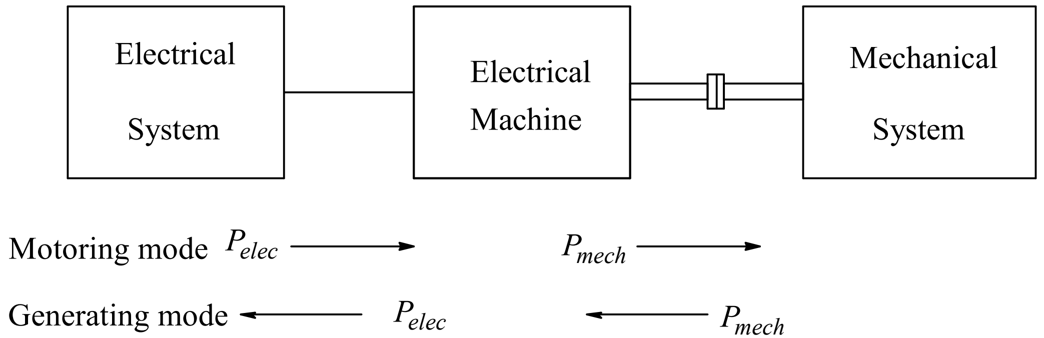


Figure 11-5 Electric machine as an energy converter.

1) A force is produced on a current-carrying conductor when it is subjected to an *externally-established* magnetic field.
2) An emf is induced in a conductor moving in a magnetic field.

Electromagnetic Force

$$\underbrace{f_{em}}_{[N]} = \underbrace{B}_{[T]}\,\underbrace{i}_{[A]}\,\underbrace{\ell}_{[m]}$$

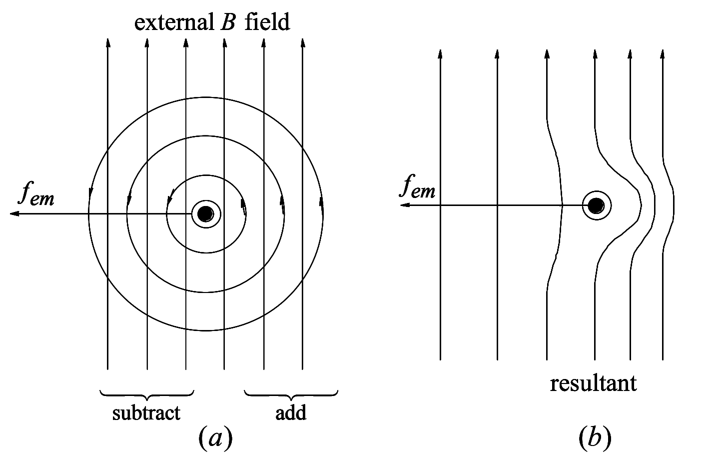


Figure 11-6 Electric force on a current-carrying conductor in a magnetic field.

Induced EMF

$$\underbrace{e}_{[V]} = \underbrace{B}_{[T]}\underbrace{l}_{[m]}\underbrace{u}_{[m/s]}$$

$$f_q = q(\mathbf{u} \times \mathbf{B})$$

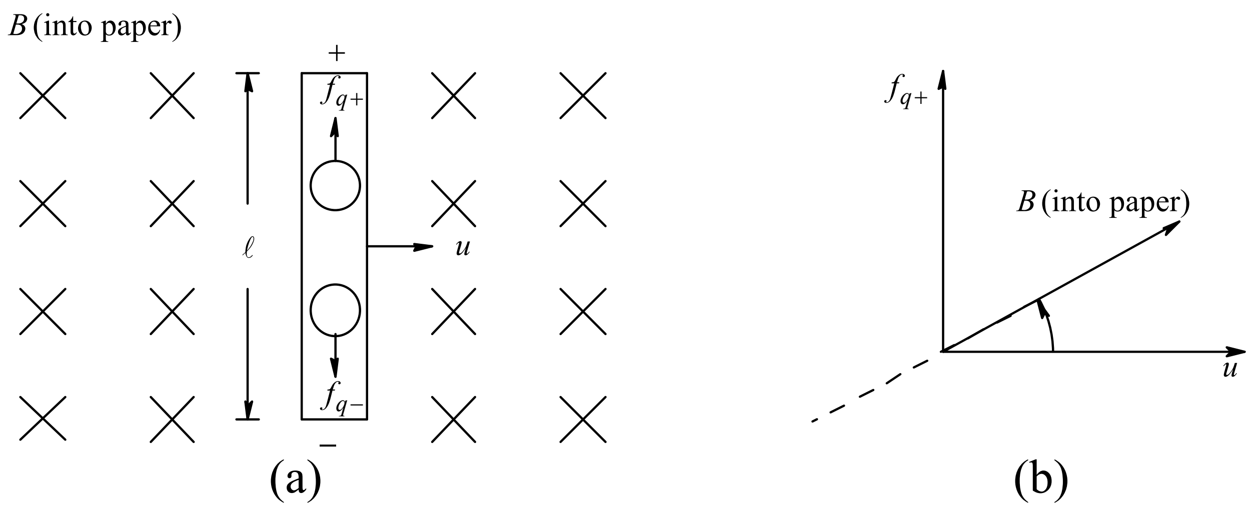


Figure 11-7 Conductor moving in a magnetic field.

Basic Structure

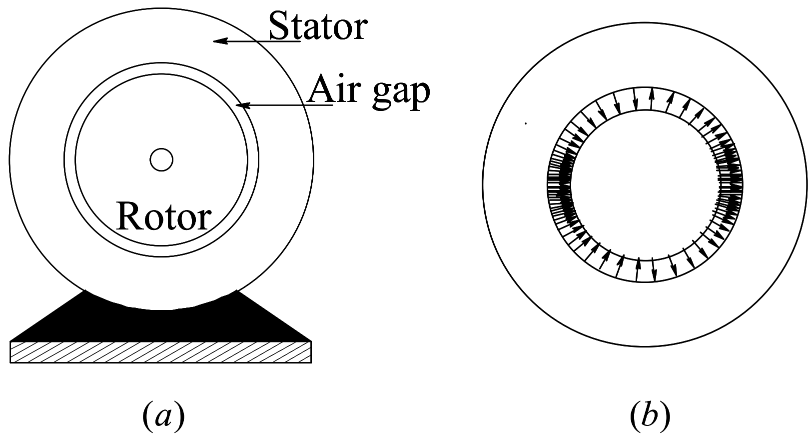


Figure 11-8 Cross-section of the machine seen from one side.

DC MOTORS

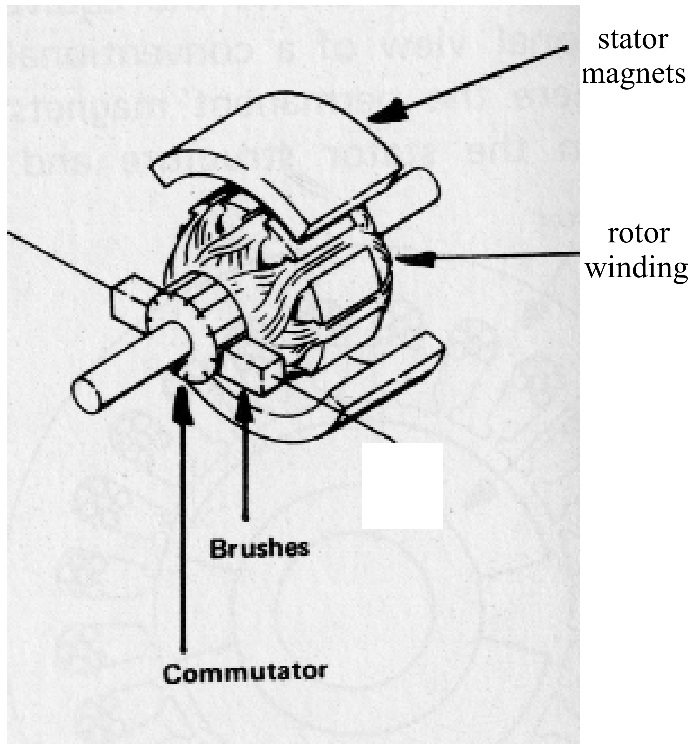


Figure 11-9 Exploded view of a dc motor; source: Engineering Handbook by Electro-Craft Corp.

Operating Principles of DC Machines

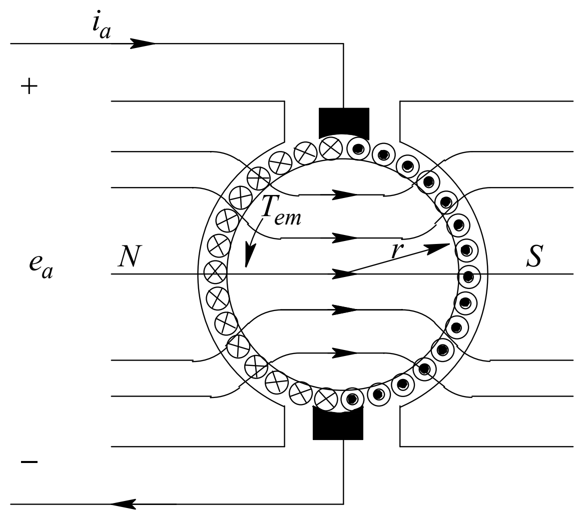


Figure 11-10 DC machine schematic representation.

$$T_{em} = k_T \, i_a$$

$$e_a = k_E \, \omega_m$$

$$k_T = k_E$$

DC-Machine Equivalent Circuit

$$v_a = e_a + R_a\,\mathrm{i}_a + L_a \frac{di_a}{dt}$$

$$\frac{d\omega_m}{dt} = \frac{1}{J_{eq}}(T_{em} - T_L)$$

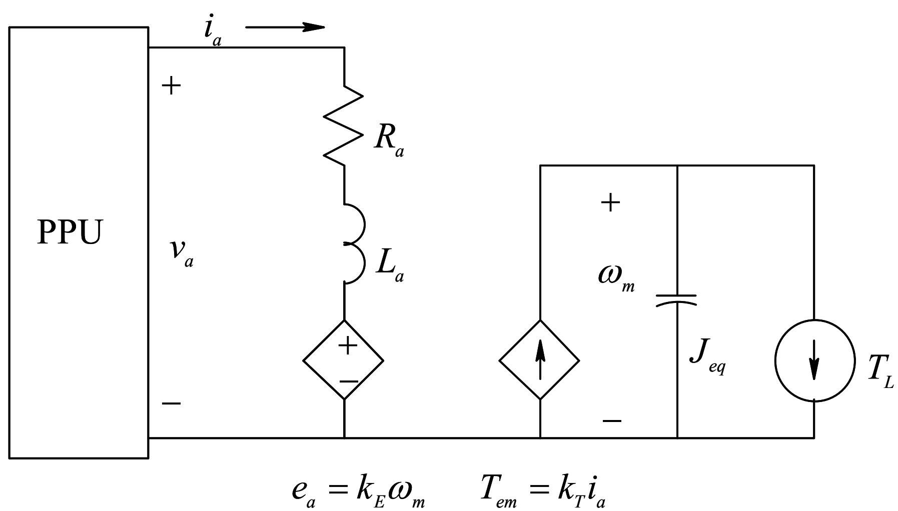


Figure 11-11 DC motor equivalent circuit.

Torque-Speed Characteristics

$$I_a = \frac{T_{em}(=T_L)}{k_T}$$

$$\omega_m = \frac{E_a}{k_E} = \frac{V_a - R_a I_a}{k_E} = \frac{V_a - R_a\left(T_{em}/k_T\right)}{k_E}$$

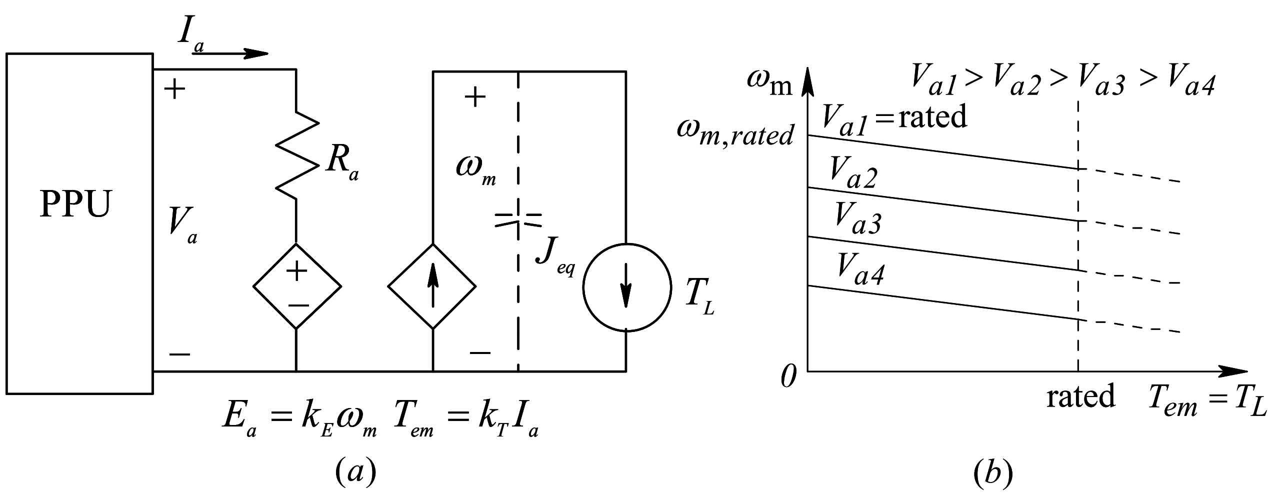


Figure 11-12 DC motor in the dc steady state.

PERMANENT-MAGNET AC MACHINES

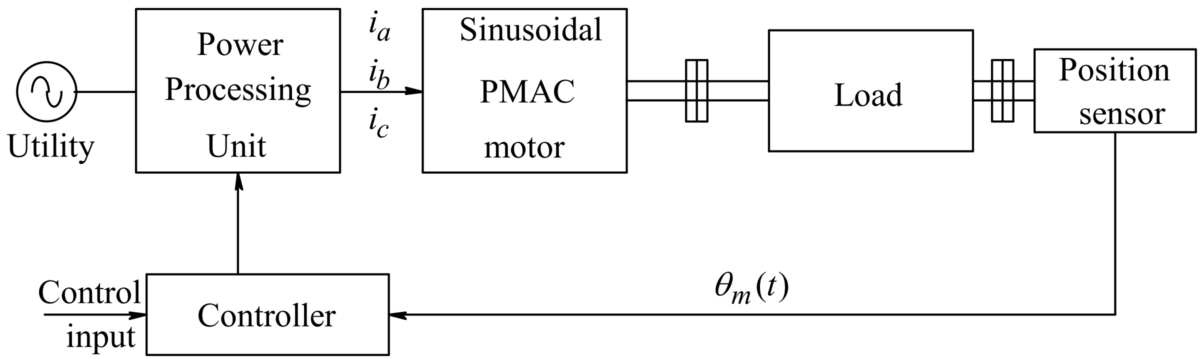


Figure 11-13 Block diagram of the closed loop operation of a PMAC drive.

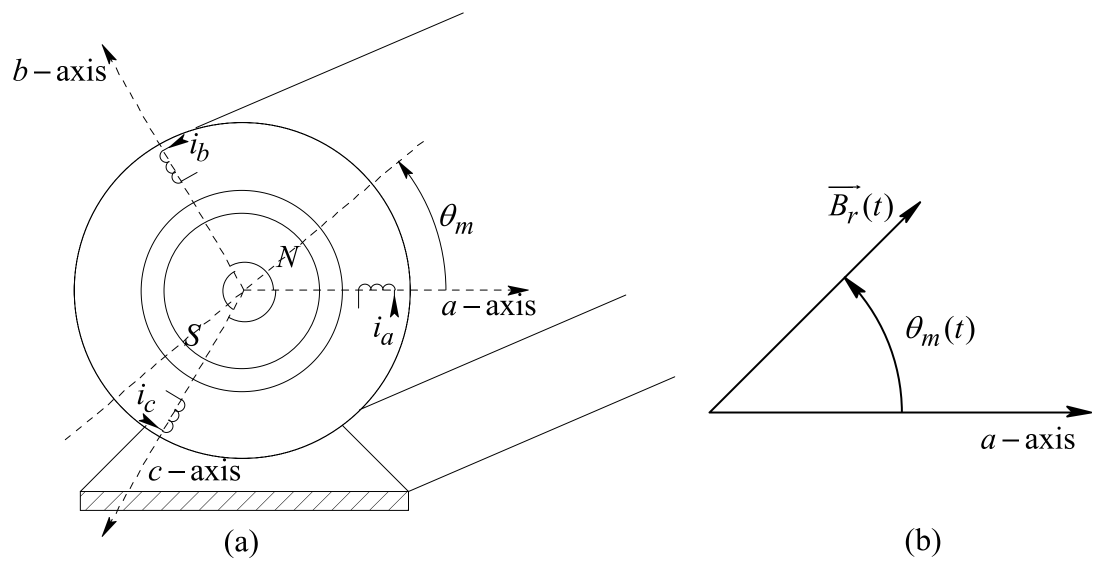


Figure 11-14 Two-pole PMAC machine.

$$\overline{E}_{ma} = E_{rms}\angle 0^0 \qquad E_{rms} = k_{E,phase}\,\omega_m \qquad \overline{I}_a = I_{rms}\angle 0^0$$

$$T_{em}\omega_m = 3\underbrace{\left(k_{E,phase}\,\omega_m\right)}_{E_{rms}} I_{rms} \qquad T_{em,1-phase} = \frac{T_{em}}{3} = k_{T,phase} I_{rms} \qquad k_{T,phase} = k_{E,phase}$$

$$\frac{d\omega_m}{dt} = \frac{T_{em} - T_L}{J_{eq}} \quad \Rightarrow \quad \omega_m(t) = \omega_m(0) + \frac{1}{J_{eq}}\int_o^t \left(T_{em} - T_L\right)\cdot d\tau$$

$$\theta_m(t) = \theta_m(0) + \int_o^t \omega_m(\tau)\cdot d\tau$$

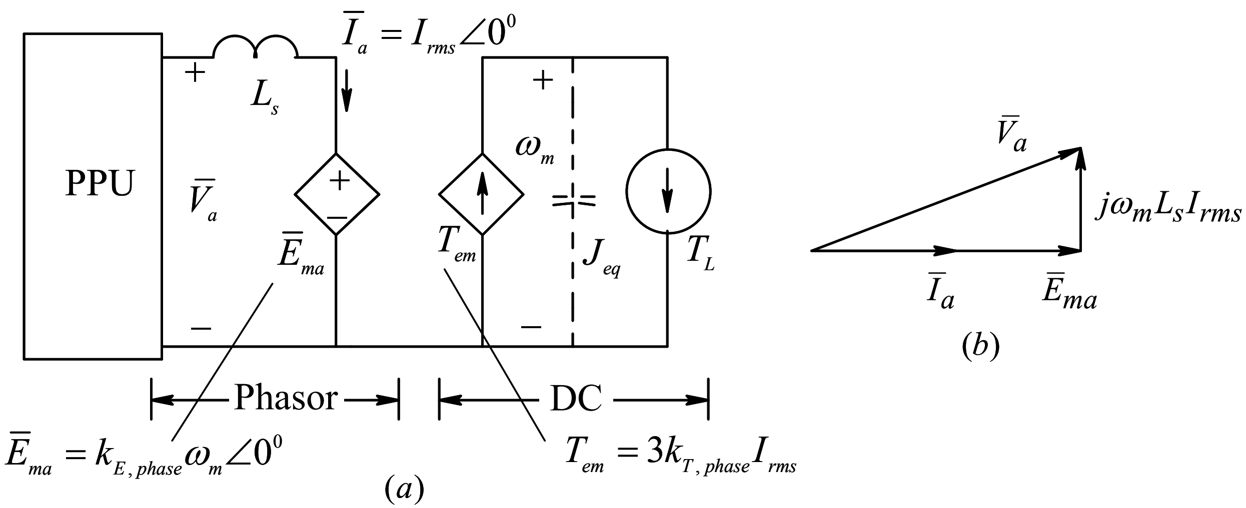


Figure 11-15 Equivalent circuit diagram and the phasor diagram of PMAC (2 pole).

PMAC Torque-Speed Characteristics

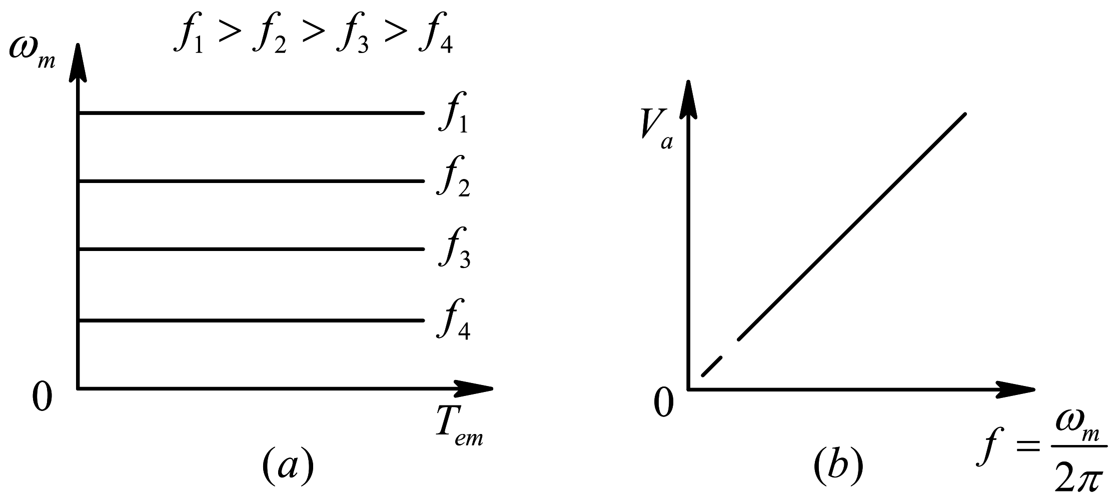
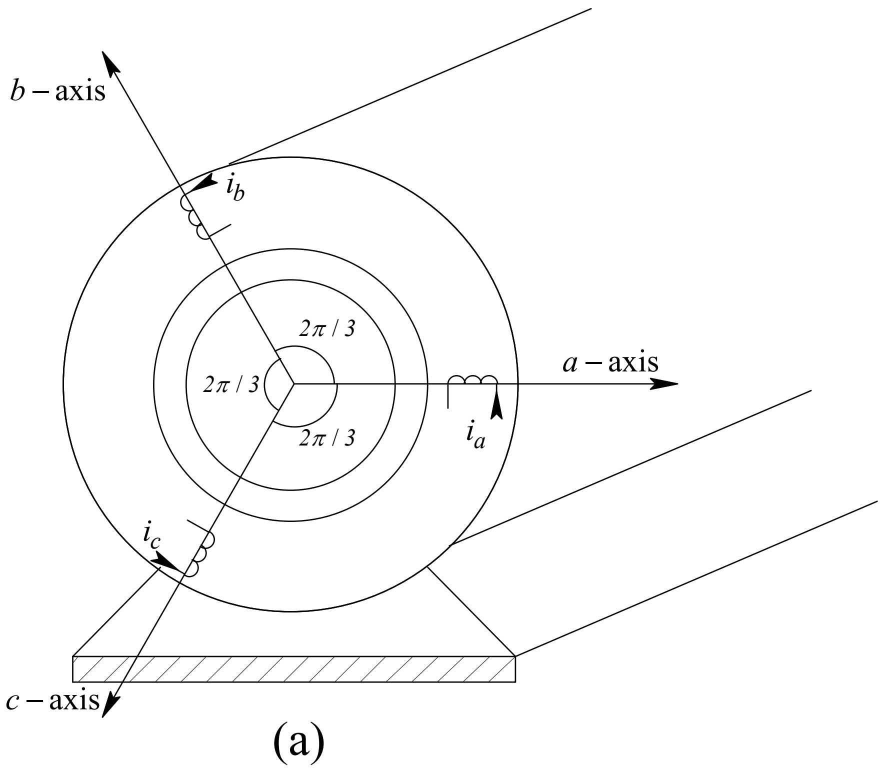


Figure 11-16 Torque-speed characteristics and the voltage versus frequency in PMAC.

Induction Machines



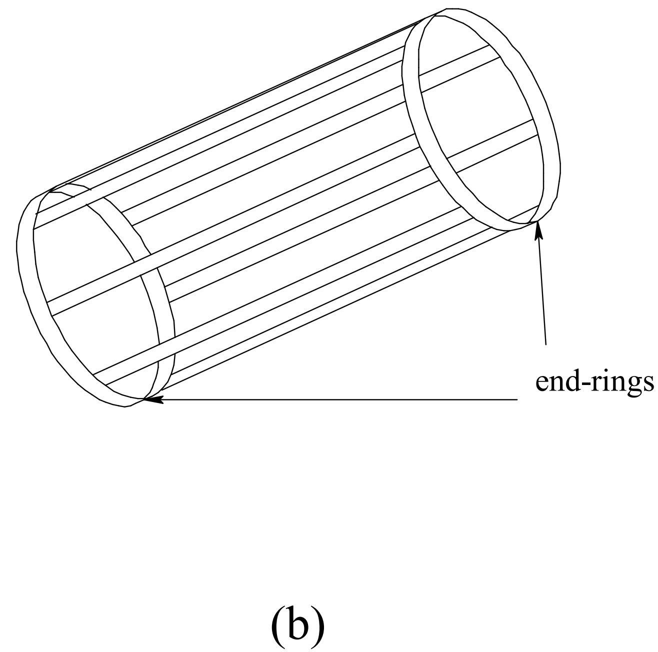


Figure 11-17 (a) Three-phase stator; (b) squirrel-cage rotor.

Principles of Induction Motor Operation

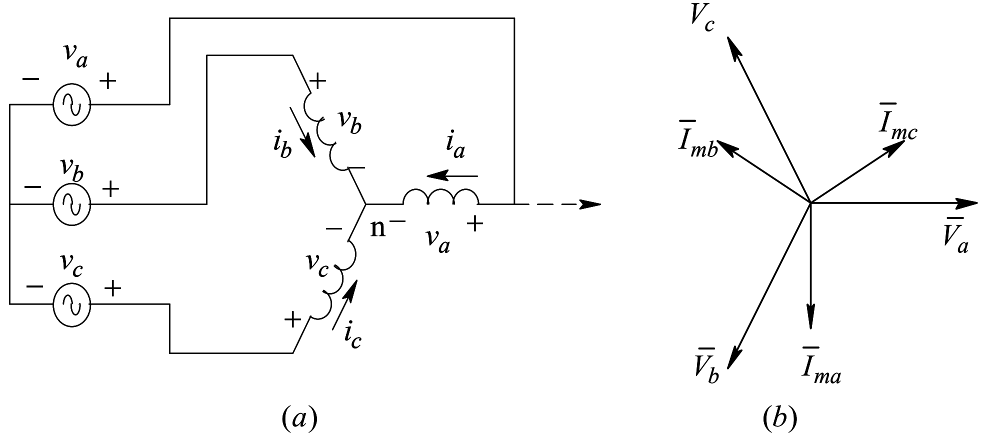


Figure 11-18 Induction machine: applied voltages and magnetizing currents.

$$\bar{V}_a = V_{rms} \angle 0^o, \quad \bar{V}_b = V_{rms} \angle -120^o, \text{ and } \quad \bar{V}_c = V_{rms} \angle -240^o$$

$$\bar{I}_{ma} = \mathrm{I}_m \angle -90^o, \quad \bar{I}_{mb} = \mathrm{I}_m \angle -210^o, \text{ and } \quad \bar{I}_{mc} = \mathrm{I}_m \angle -330^o$$

$$\omega_{syn} = 2\pi f \qquad \omega_{syn} = \frac{2\pi f}{p/2} \quad \text{for a } p\text{-pole machine}$$

$$\textit{slip speed} \quad \omega_{slip} = \omega_{syn} - \omega_m \qquad \textit{slip frequency} \quad f_{slip} = \frac{\omega_{slip}}{\omega_{syn}} f$$

Per-Phase Equivalent Circuit of Induction Machines

$$\bar{V}_a = \bar{E}_{ma} = k_{E,phase}\omega_{syn}\angle 0^0 \qquad \bar{I}'_{ra} = I'_{ra}\angle 0^0 \qquad T_{em,phase} = k_{T,phase}I'_{ra}$$

$$P_{em,phase} = \omega_m T_{em,phase} = \omega_m k_{T,phase} I'_{ra} \qquad \bar{E}'_a = \omega_m k_{E,phase}\angle 0^0 \qquad k_{T,phase} = k_{E,phase}$$

$$\bar{V}'_{ra} = \underbrace{k_{E,phase}\omega_{syn}\angle 0^0}_{\bar{E}_{ma}} - \underbrace{k_{E,phase}\omega_m\angle 0^0}_{\bar{E}'_a} = k_{E,phase}\omega_{slip}\angle 0^0$$

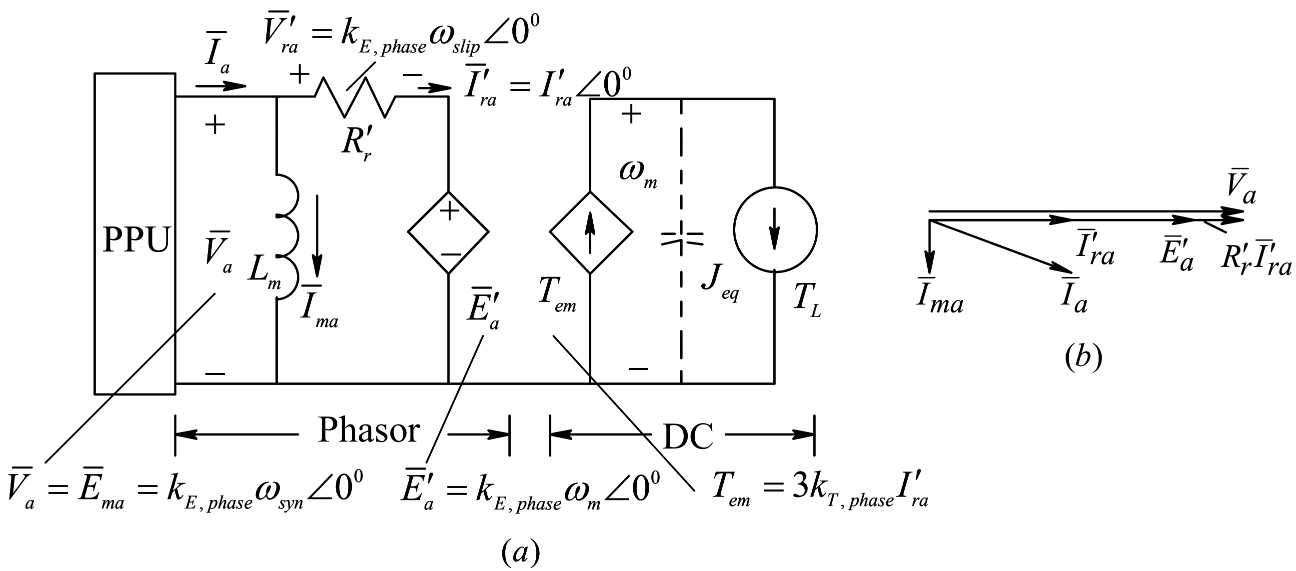


Figure 11-19 Induction motor equivalent circuit and phasor diagram.

$$I'_{ra} = \left(\frac{k_{E,phase}}{R'_r} \right) \omega_{slip}$$

$$T_{em} = \frac{P_{em}}{\omega_m} = \underbrace{\left(3\frac{k^2_{T,phase}}{R'_r} \right)}_{k_{T,\omega_{slip}}} \omega_{slip}$$

$$\omega_m = \omega_{syn} - \frac{T_{em}}{k_{T,\omega_{slip}}}$$

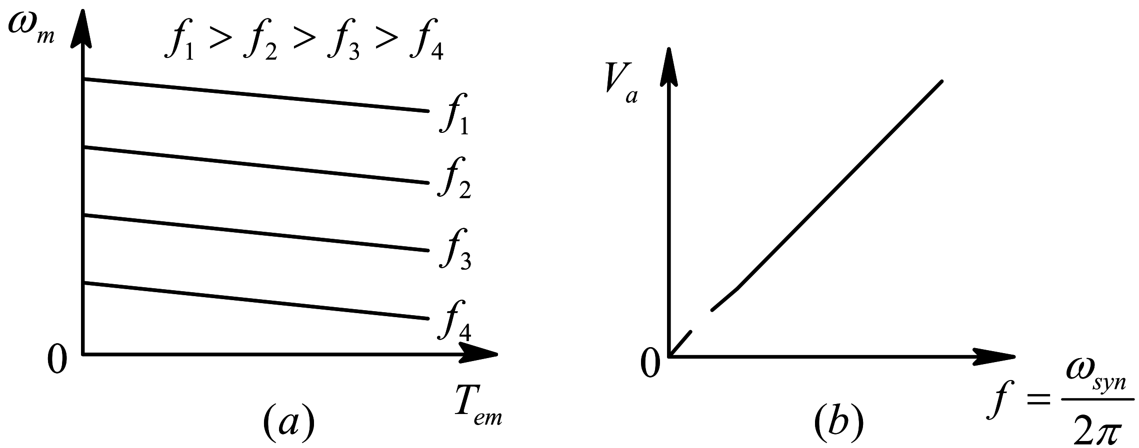


Figure 11-20 Induction motors: Torque-speed characteristics and voltage vs. frequency.