Chapter 14

Induction Motor Drives

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- Extremely large potential as adjustable speed drives

Pump Application: Adjustable Flow rate

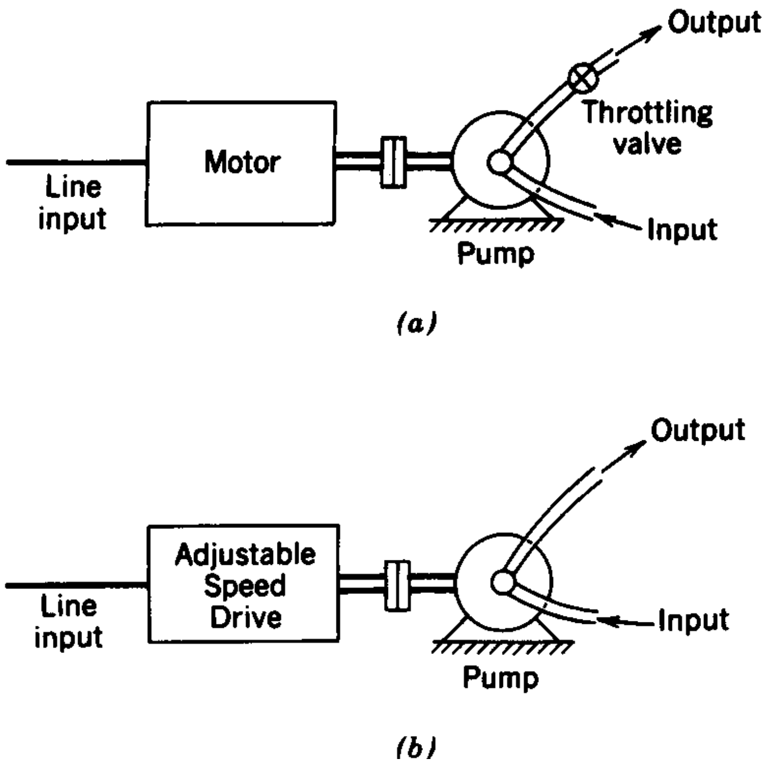

Figure 14-1 Centrifugal pump: (*a*) constant-speed drive: (*b*) adjustable-speed drive.

- Fixed versus adjustable speed drive

Per-Phase Representation

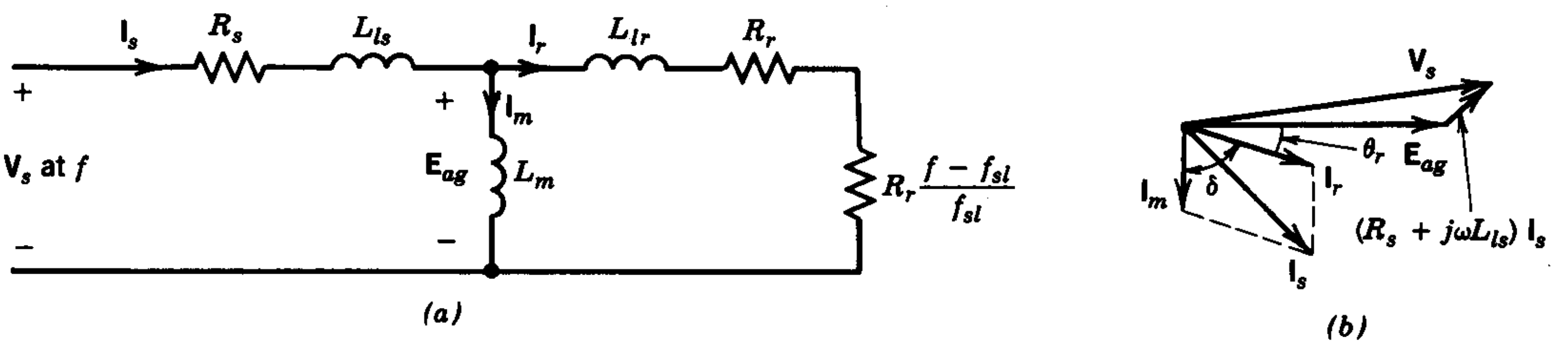

Figure 14-2 Per-phase representation: (*a*) equivalent circuit; (*b*) phasor diagram.

- Assuming sinusoidal steady state

Important Relationships in an Induction Machine

Table 14-1 Important Relationships

$\omega_s = k_7 f$	
$s = \dfrac{\omega_s - \omega_r}{\omega_s}$	
$f_{sl} = sf$	
$\%P_r = \dfrac{f_{sl}}{f - f_{sl}}$	
$V_s \simeq k_3 \phi_{ag} f$	
$I_r \simeq k_5 \phi_{ag} f_{sl}$	
$T_{em} \simeq k_6 \phi_{ag}^2 f_{sl}$	
$I_m = k_8 \phi_{ag}$	(from Eq. 14-5)
$I_s \simeq \sqrt{I_m^2 + I_r^2}$	

- Not necessary for our purposes to know the exact expressions for constants used here

Torque-Speed Characteristics

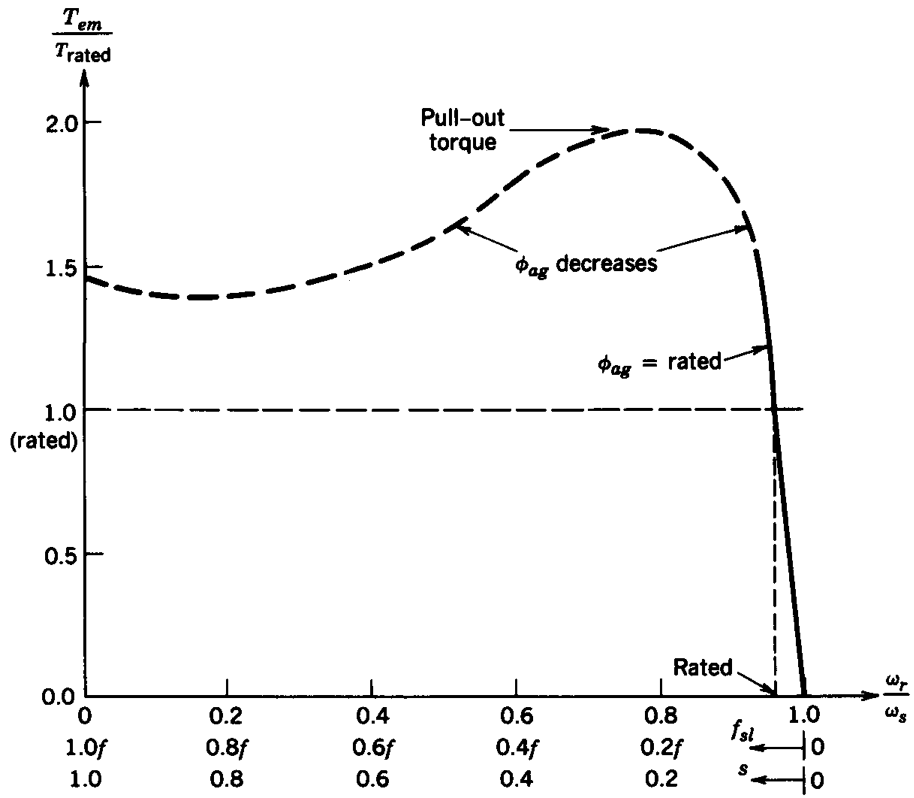

Figure 14-3 A typical torque–speed characteristic; V_s and f are constant at their rated values.

- The linear part of the characteristic is utilized in adjustable speed drives

Plot of Normalized Rotor Current

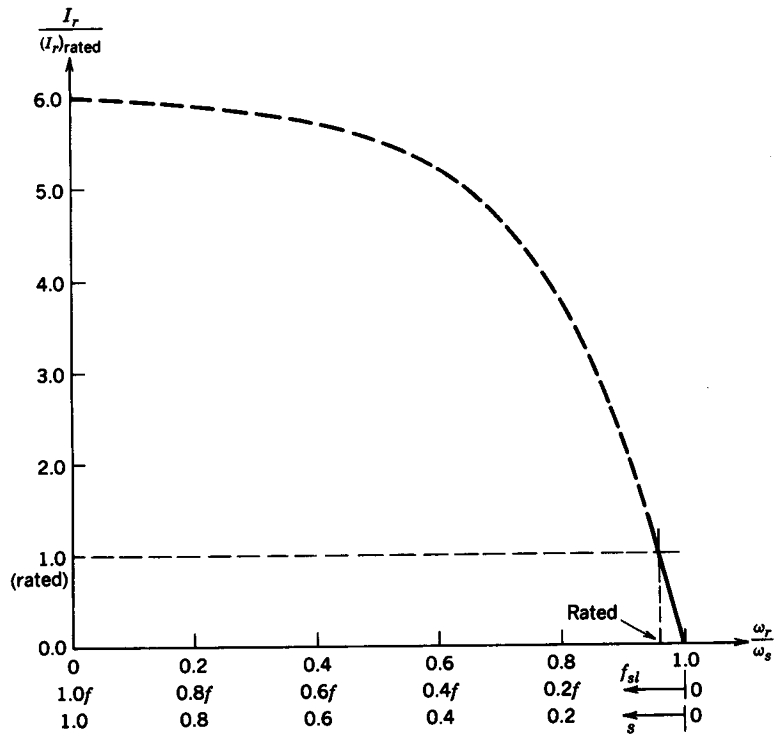

Figure 14-4 Plot of I_r versus f_{sl}; V_s and f are constant at their rated values.

- It increases with slip and slip frequency

Acceleration Torque at Startup

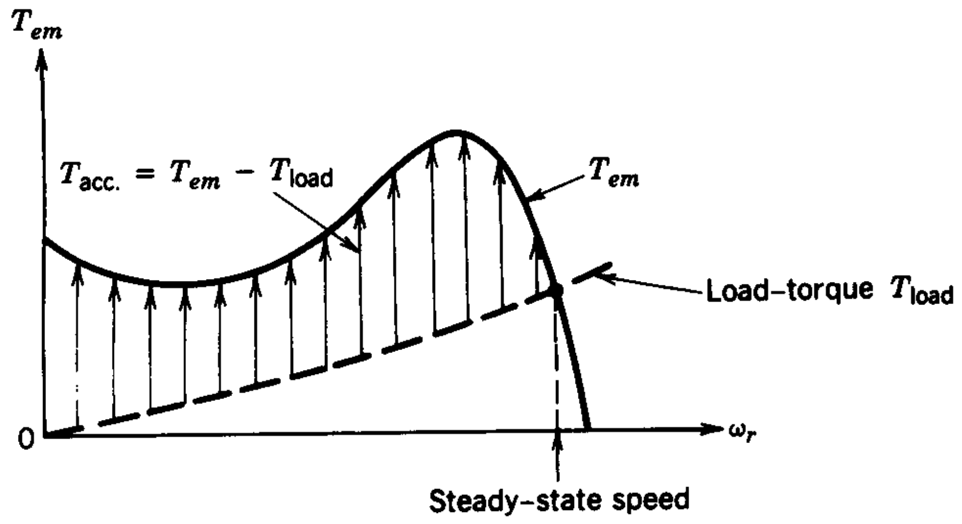

Figure 14-5 Motor start-up; V_s and f are constant at their rated values.

- Intersection represents the equilibrium point

Torque Speed Characteristics at various Frequencies of Applied Voltage

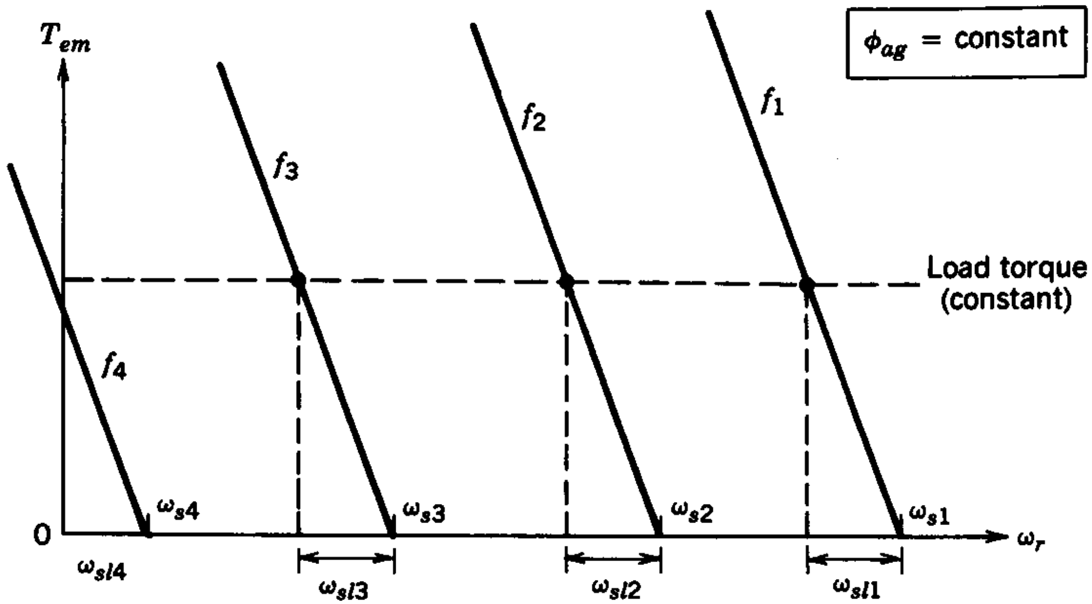

Figure 14-6 Torque–speed characteristics at small slip with a constant ϕ_{ag}; constant load torque.

- The air gap flux is kept constant

Adjusting Speed of a Centrifugal Load

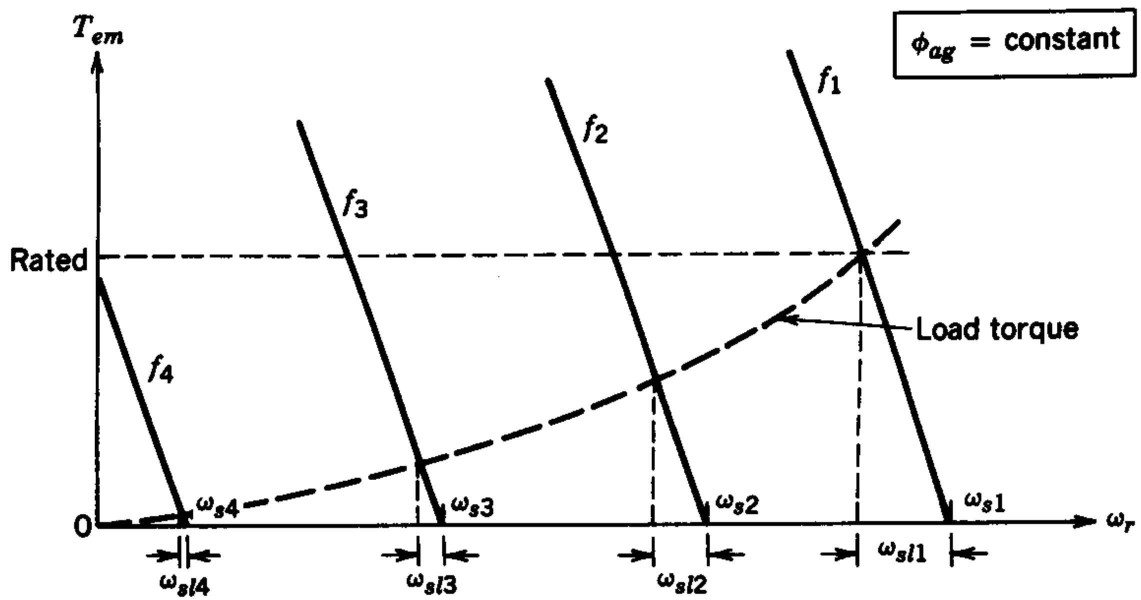

Figure 14-7 Centrifugal load torque; torque varies as the speed squared.

- The load torque is proportional to speed squared

Frequency at Startup

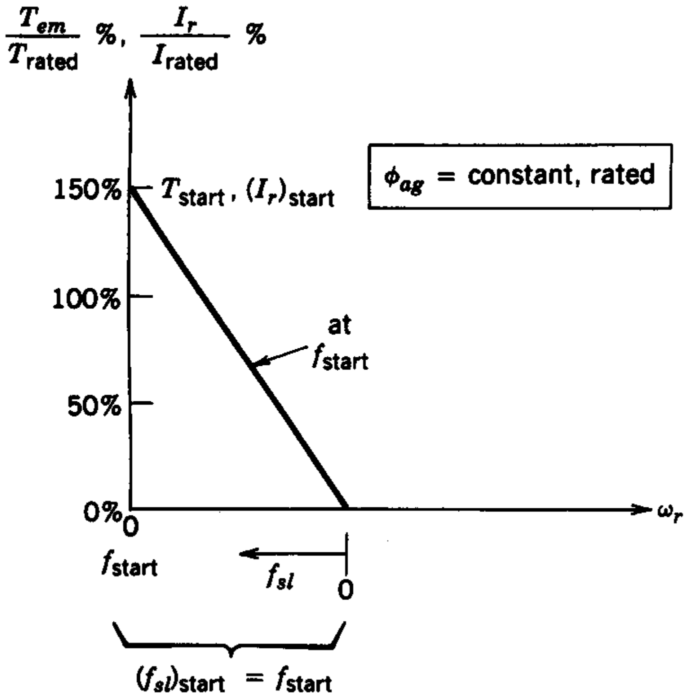

Figure 14-8 Frequency at start-up.

- The torque is limited to limit current draw

Increasing Speed at Startup

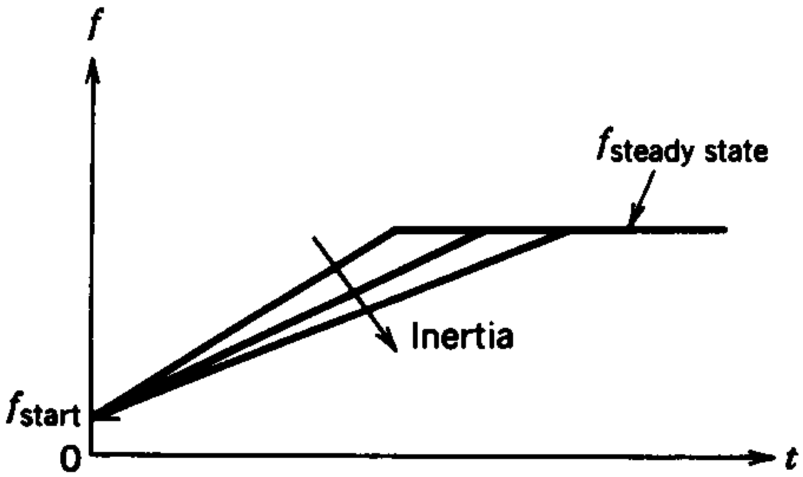

Figure 14-9 Ramping of frequency f at start-up.

- The ramp rate of frequency depends on load inertia

Phasor Diagram at Small Value of Slip Frequency

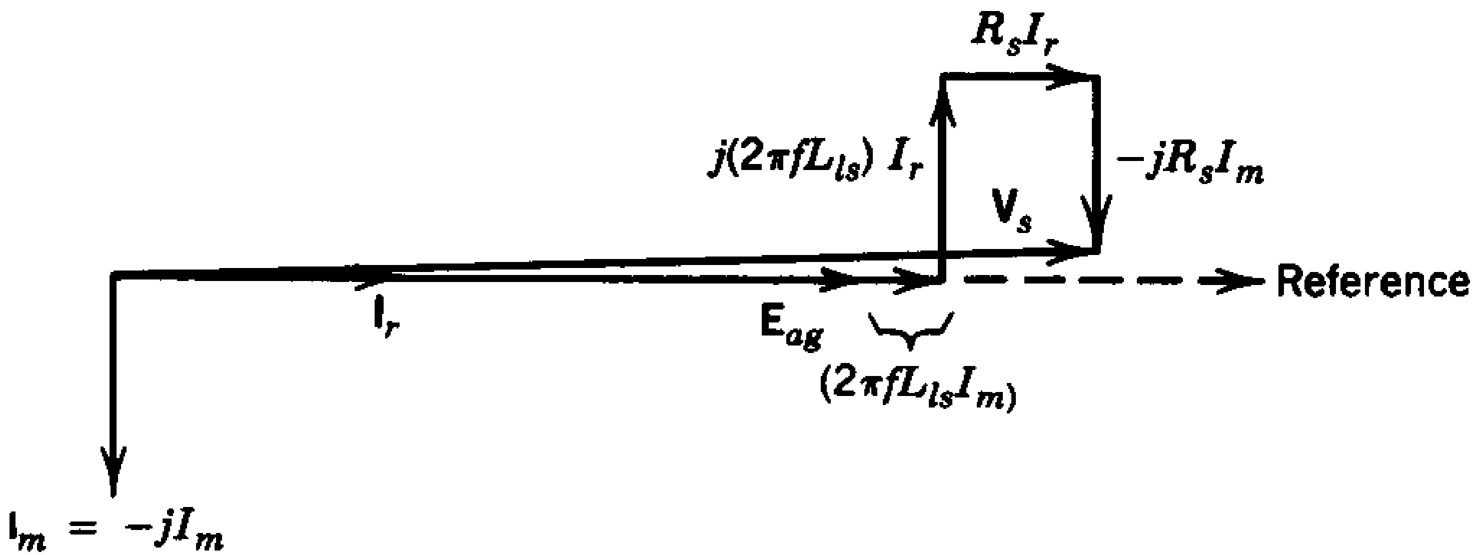

Figure 14-10 Phasor diagram at a small value of f_{sl}.

- The rotor branch is assumed to be purely resistive

Voltage Boost to Keep Air Gap Flux at its Rated Value

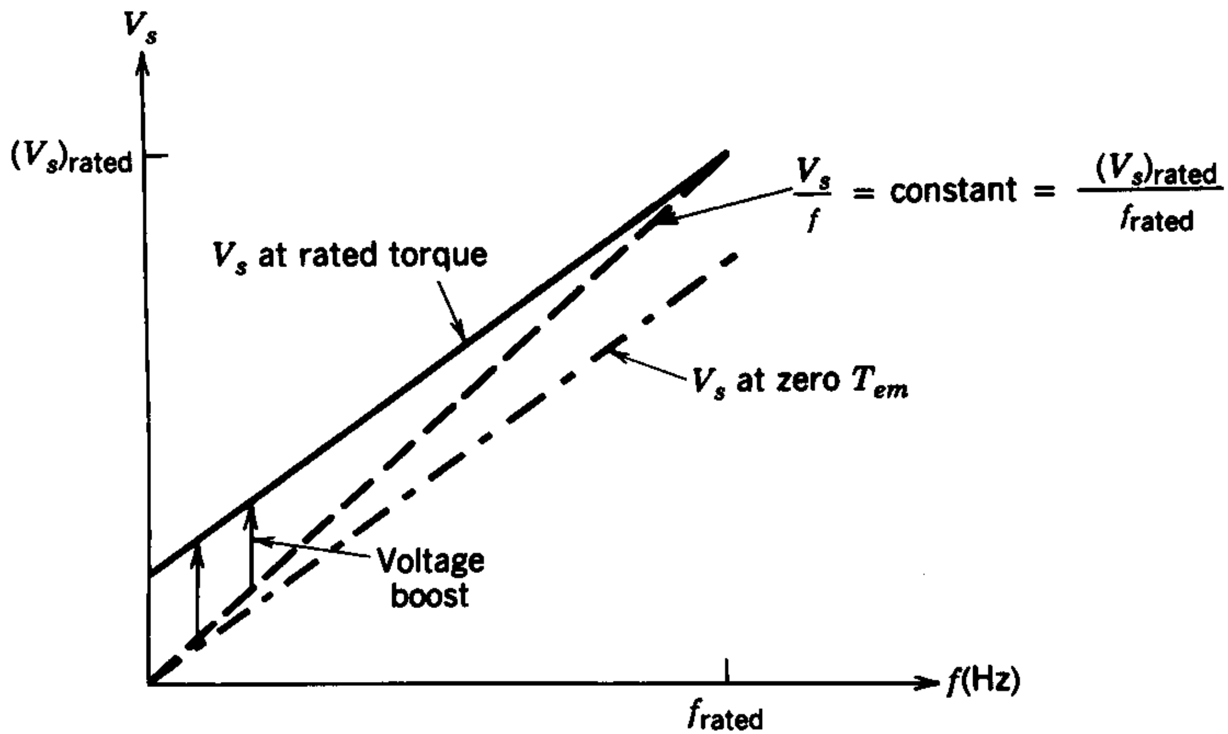

Figure 14-11 Voltage boost required to keep ϕ_{ag} constant.

- Depends on the torque loading of the machine

Induction Motor Drive Capability Curves

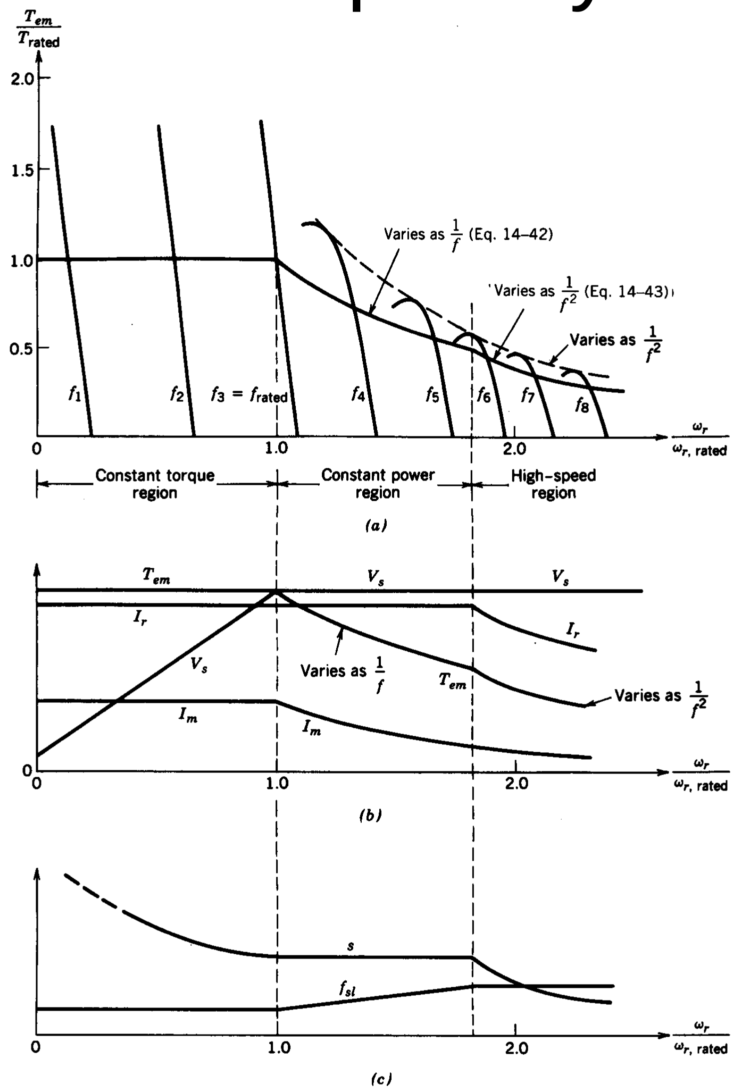

Figure 14-12 Induction motor characteristics and capabilities.

- Mainly two regions

Generator Mode of Operation

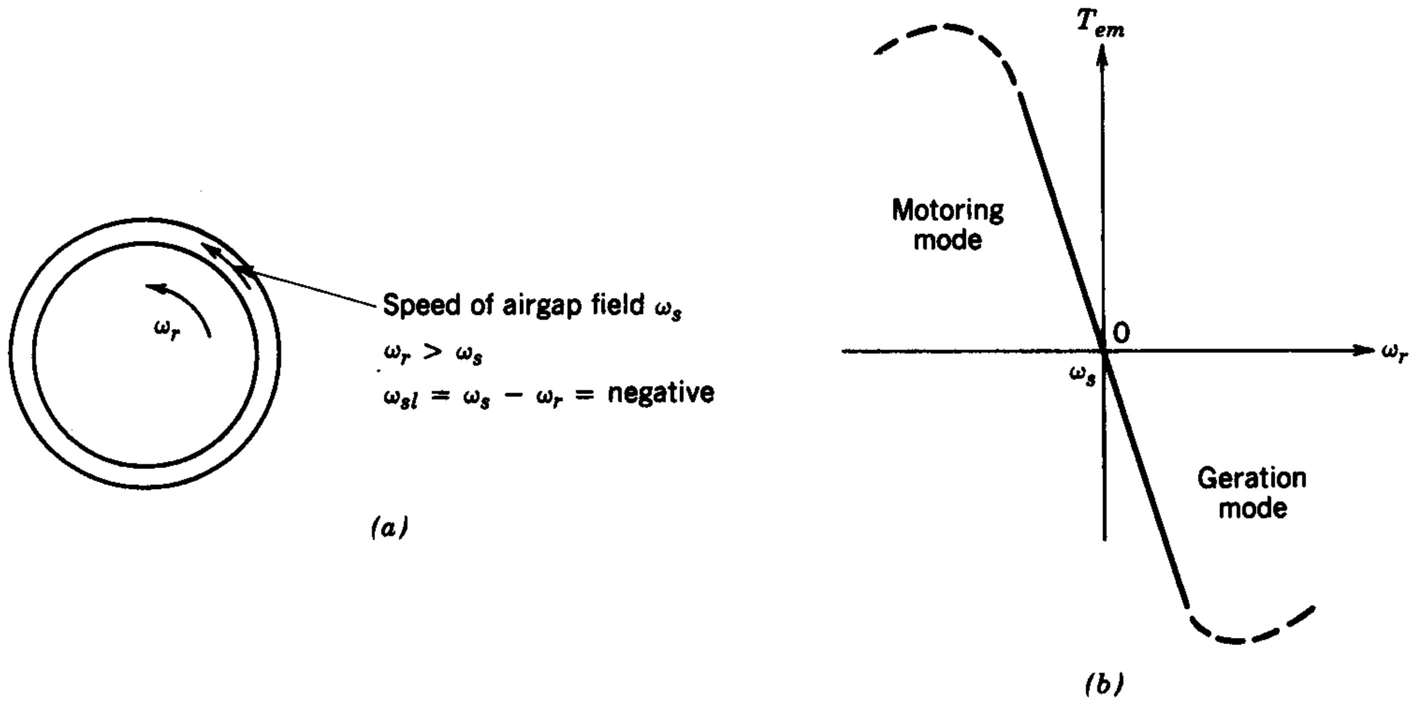

Figure 14-13 Generation mode.

- Rotor speeds exceed the synchronous speed

Regenerative Braking Mode to Slow Down

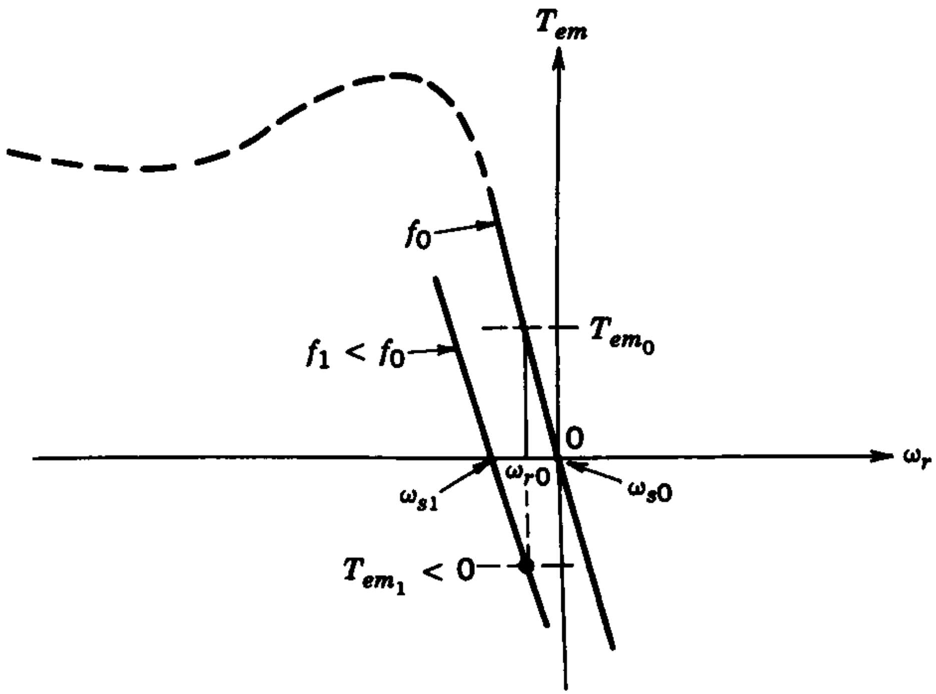

Figure 14-14 Braking (initial motor speed is ω_{r0} and the applied frequency is instantaneously decreased from f_0 to f_1).

- Machine is made to go into the generator mode

Per-Phase Equivalent Circuit at Harmonic Frequencies

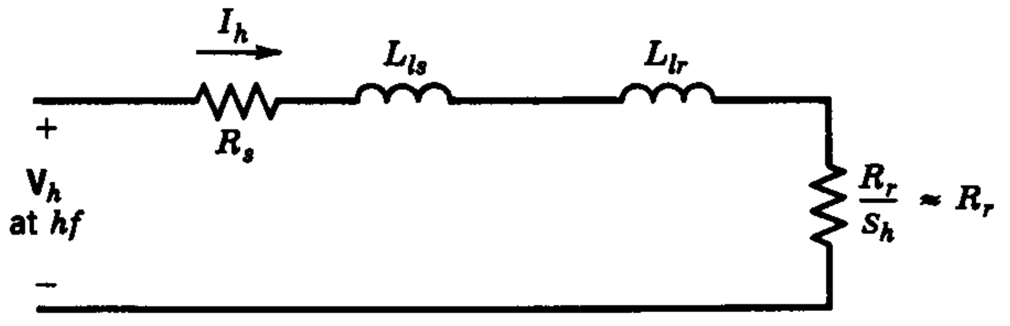

Figure 14-15 Per-phase harmonic equivalent circuit.

- The magnetizing branch is ignored

Torque Pulsations due to Harmonics

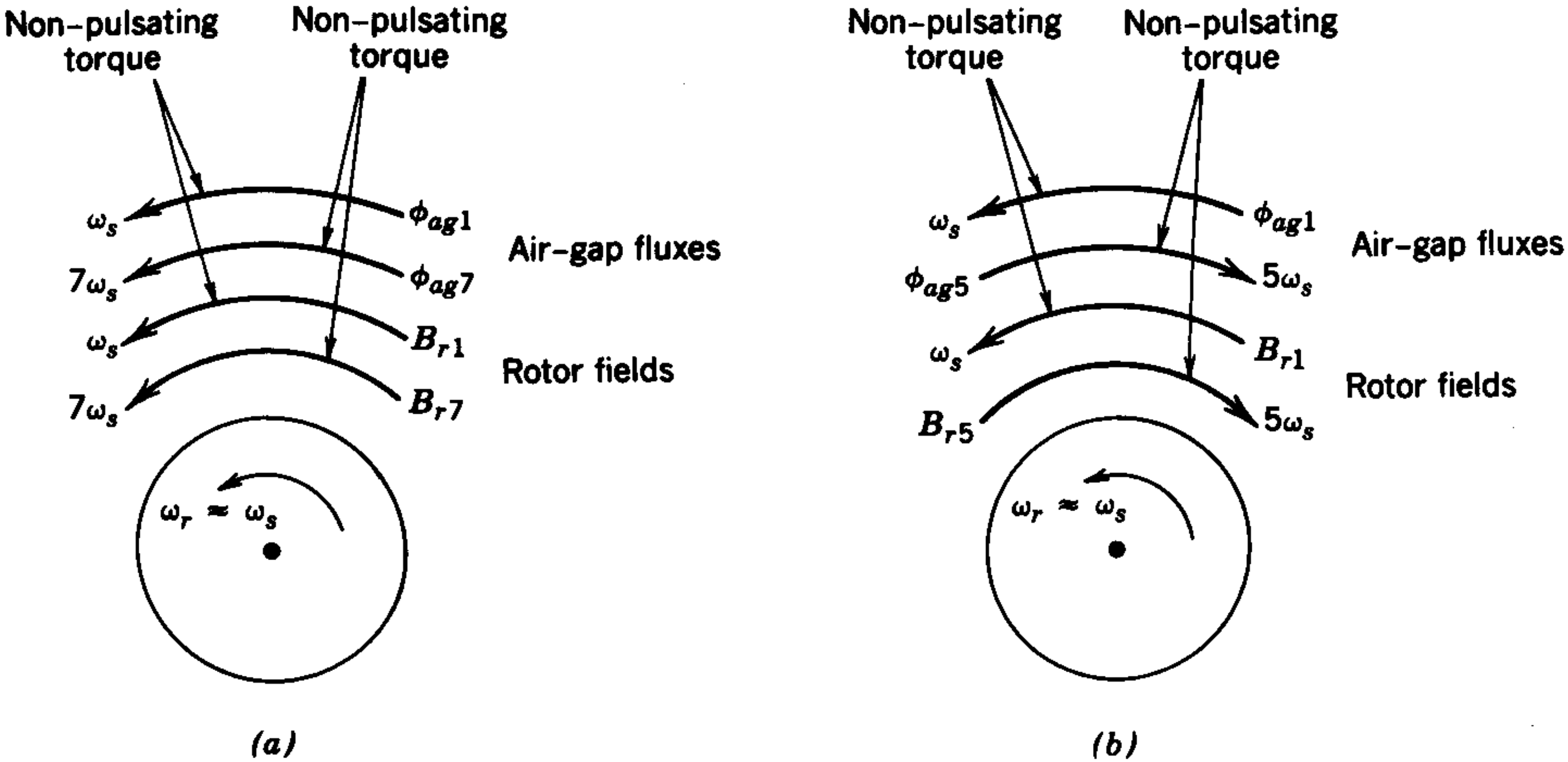

Figure 14-16 Torque pulsations: (*a*) seventh harmonic; (*b*) fifth harmonic.

- Rotations of fields due to the fifth and the seventh harmonics are in opposite directions

Classification of Converter Systems

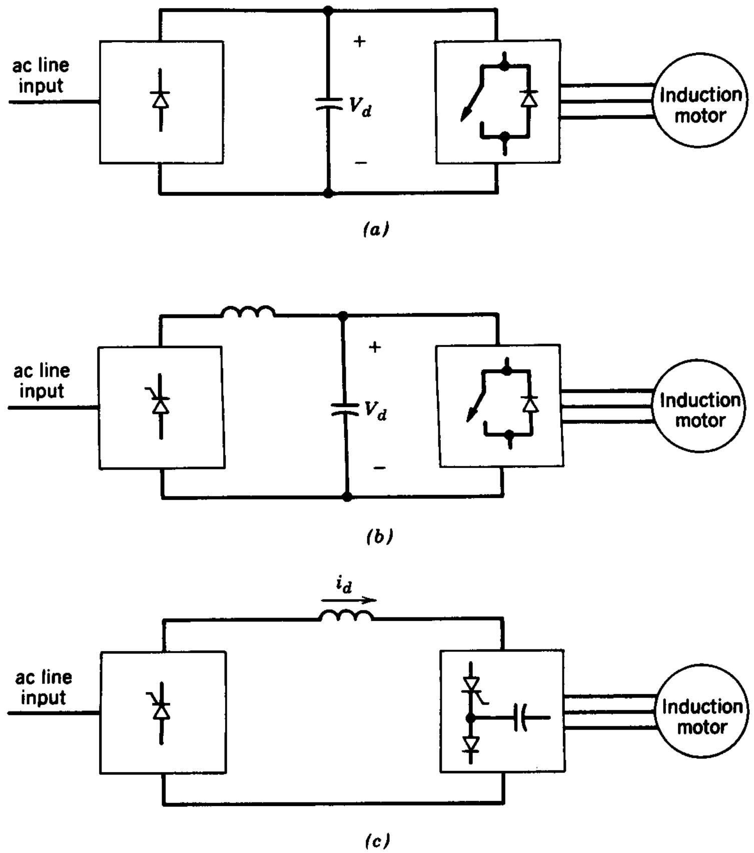

Figure 14-18 Classification of variable-frequency converters: (*a*) PWM-VSI with a diode rectifier; (*b*) square-wave VSI with a controlled rectifier; (*c*) CSI with a controlled rectifier.

- PWM-VSI is now most commonly use

PWM-VSI System

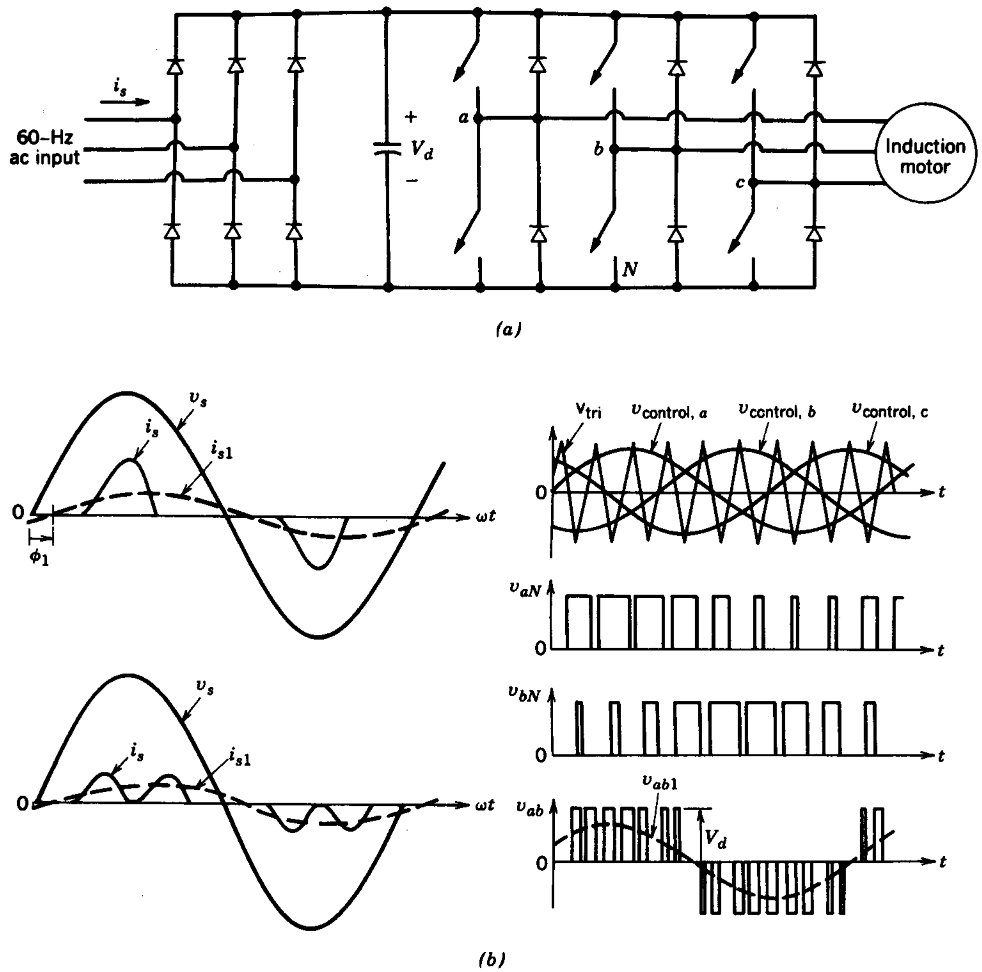

Figure 14-19 PWM-VSI: (*a*) schematic; (*b*) waveforms.

- Diode rectifier for unidirectional power flow

PWM-VSI System

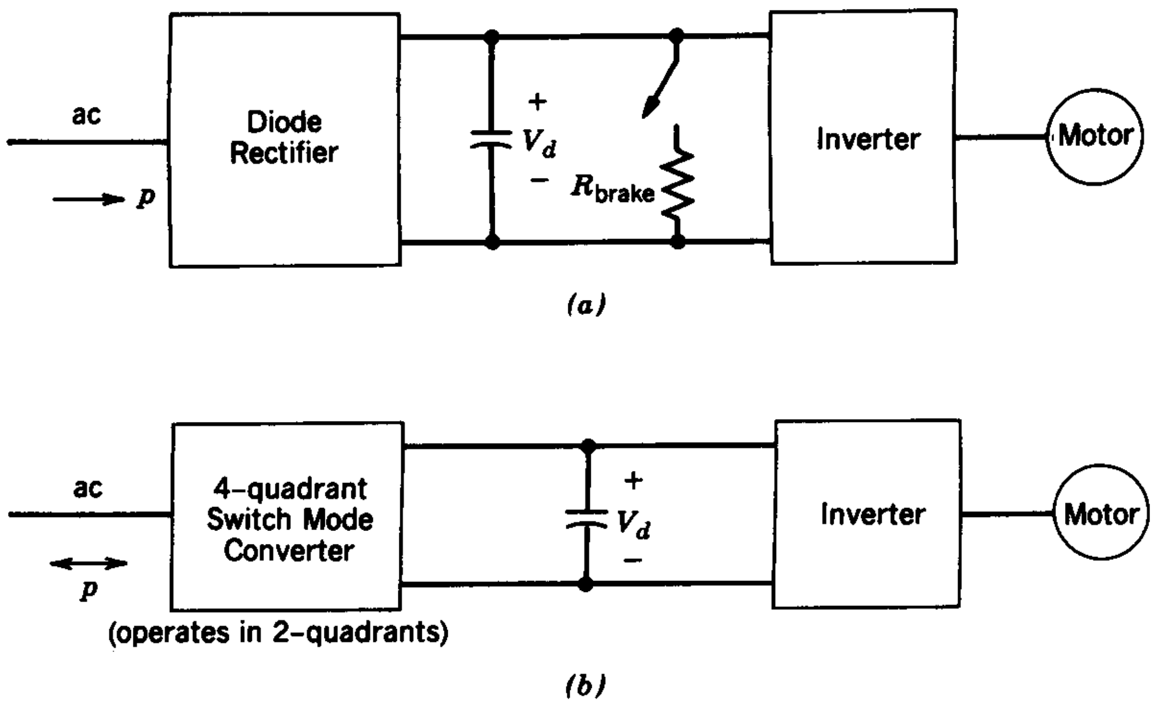

Figure 14-20 Electromagnetic braking in PWM-VSI: (*a*) dissipative braking; (*b*) regenerative braking.

- Options for recovered energy during regenerative braking

General-Purpose Speed Controller

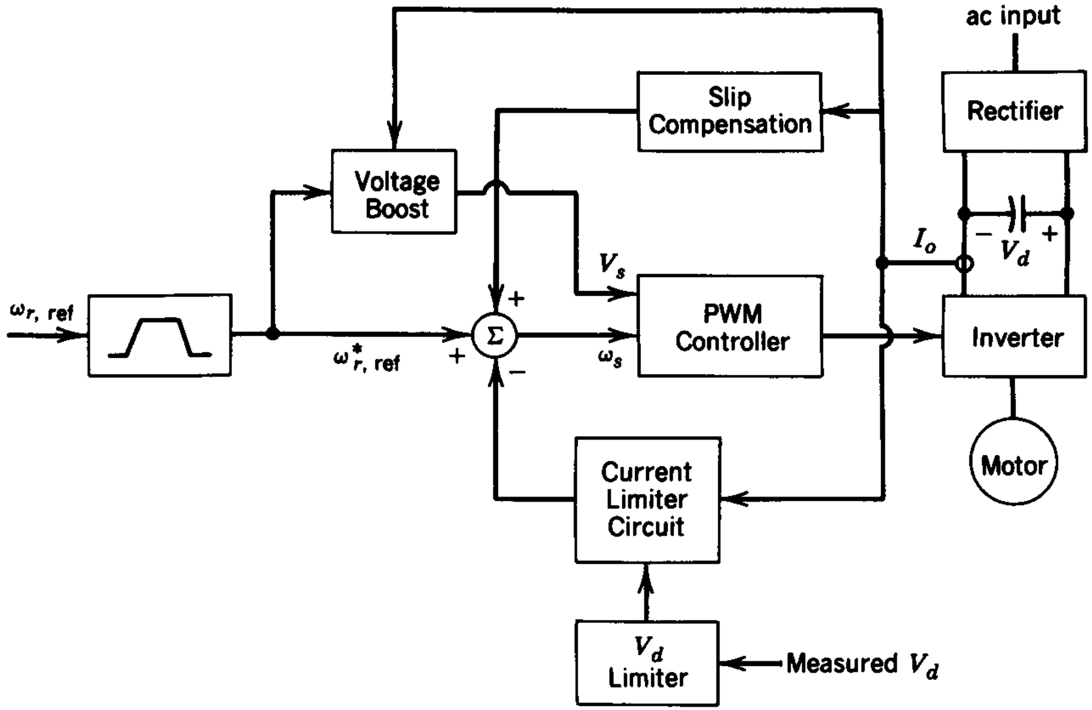

Figure 14-21 Speed control circuit. Motor speed is not measured.

- High dynamic performance is not the objective here

Change in Switching Frequency based on the required Fundamental Frequency

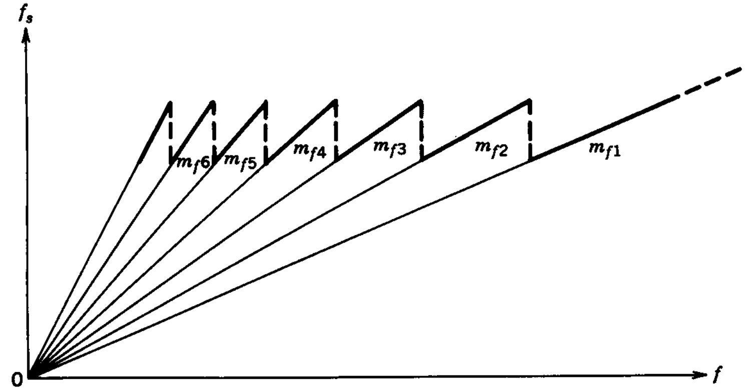

Figure 14-22 Switching frequency versus the fundamental frequency.

- Can be significant in large power ratings

Field-Oriented Control

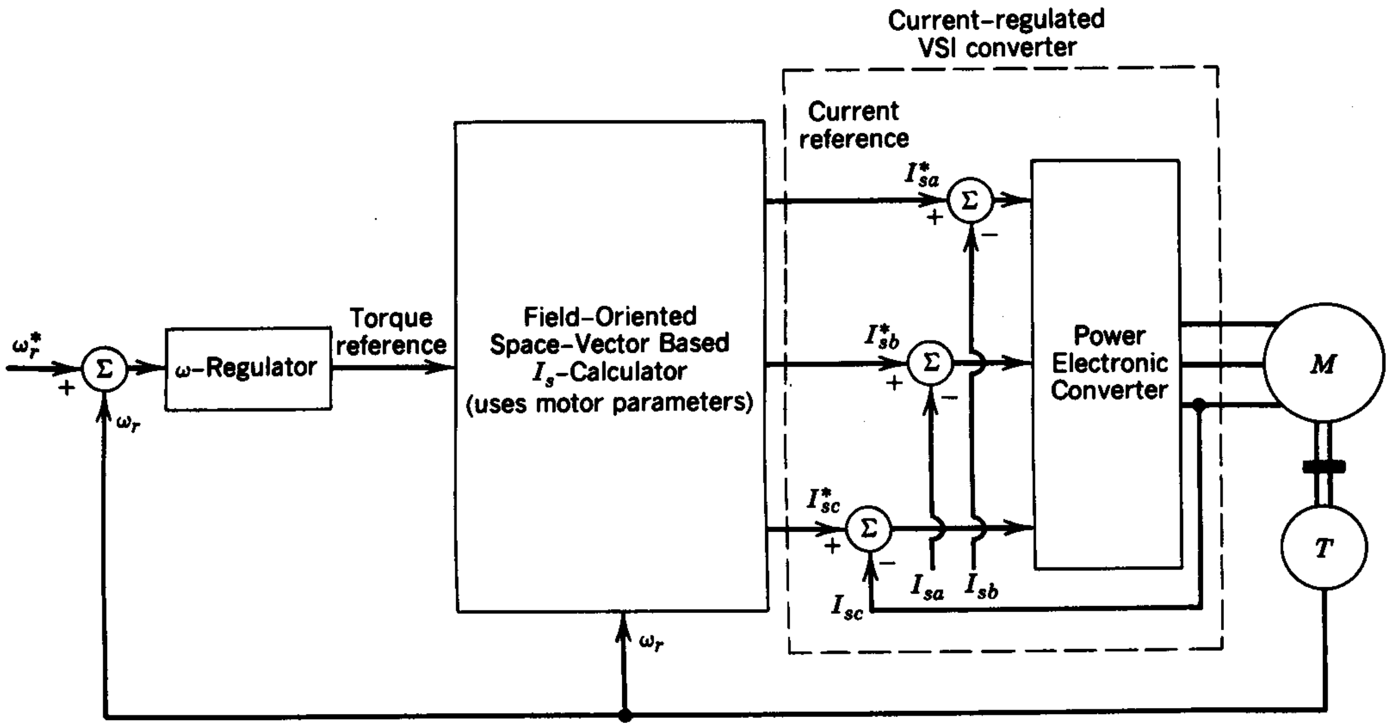

Figure 14-23 Field-oriented control for induction motor servo drive.

• A concise coverage is presented in "Advanced Electric Drives: Analysis, Control and Modeling using Simulink" by N. Mohan (www.MNPERE.com)

Square-Wave VSI Waveforms

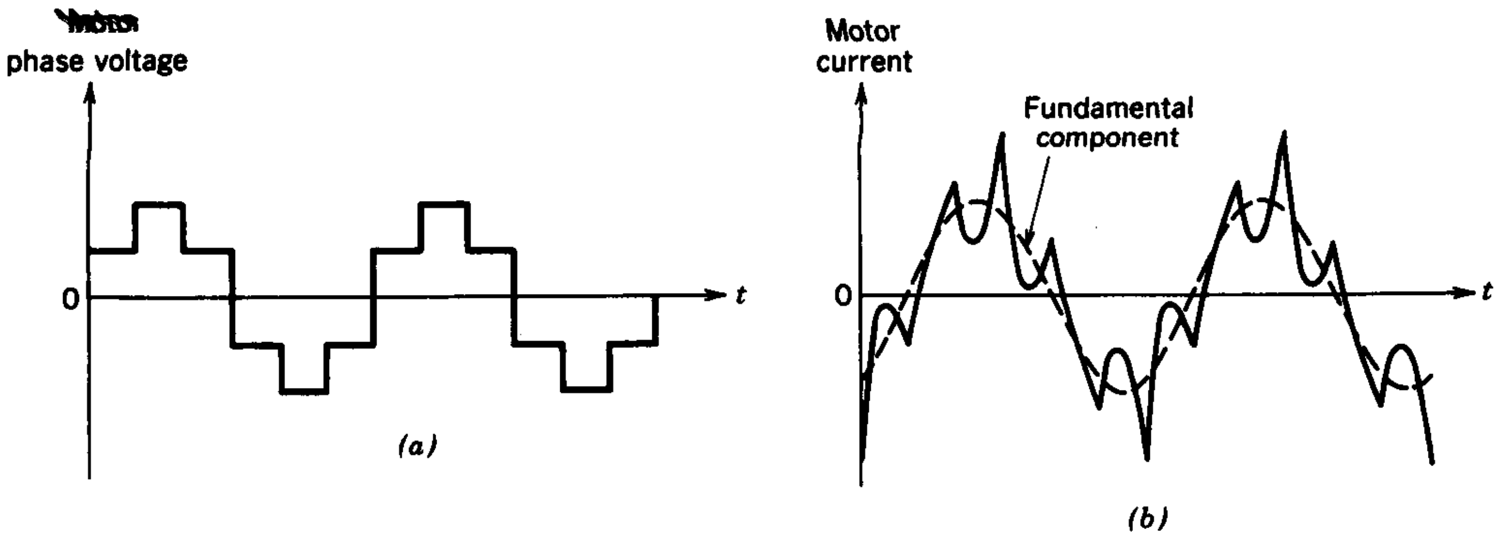

Figure 14-24 Square-wave VSI waveforms.

- Large peak-peak ripple in currents

CSI Drives

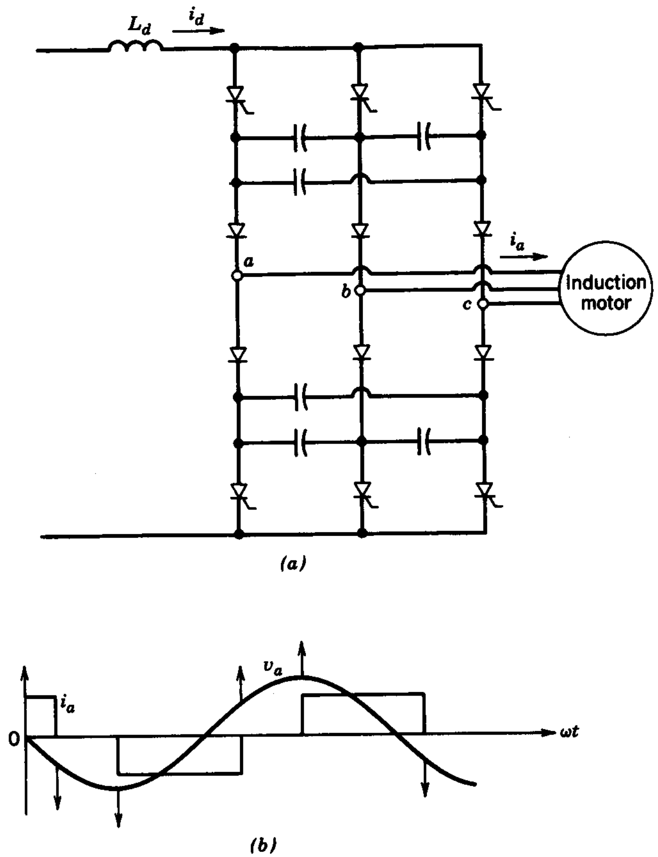

Figure 14-25 CSI drive: (*a*) inverter; (*b*) idealized phase waveforms.

- Mostly PWM-VSI drives are used

Comparison of Three Types of Inverter Systems

Table 14-2 Comparison of Adjustable Frequency Drives

Parameter	*PWM*	*Square Wave*	*CSI*
Input power factor	+	−	− −
Torque pulsations	+ +	−	−
Multimotor capability	+	+	−
Regeneration	−	−	+ +
Short-circuit protection	−	−	+ +
Open-circuit protection	+	+	−
Ability to handle undersized motor	+	+	−
Ability to handle oversized motor	−	−	−
Efficiency at low speeds	−	+	+
Size and weight	+	+	− −
Ride-through capability	+	−	−

- PWM-VSI is by far the most commonly selected system now

Speed Control by Adjusting the Stator Voltage

- Highly inefficient in most cases

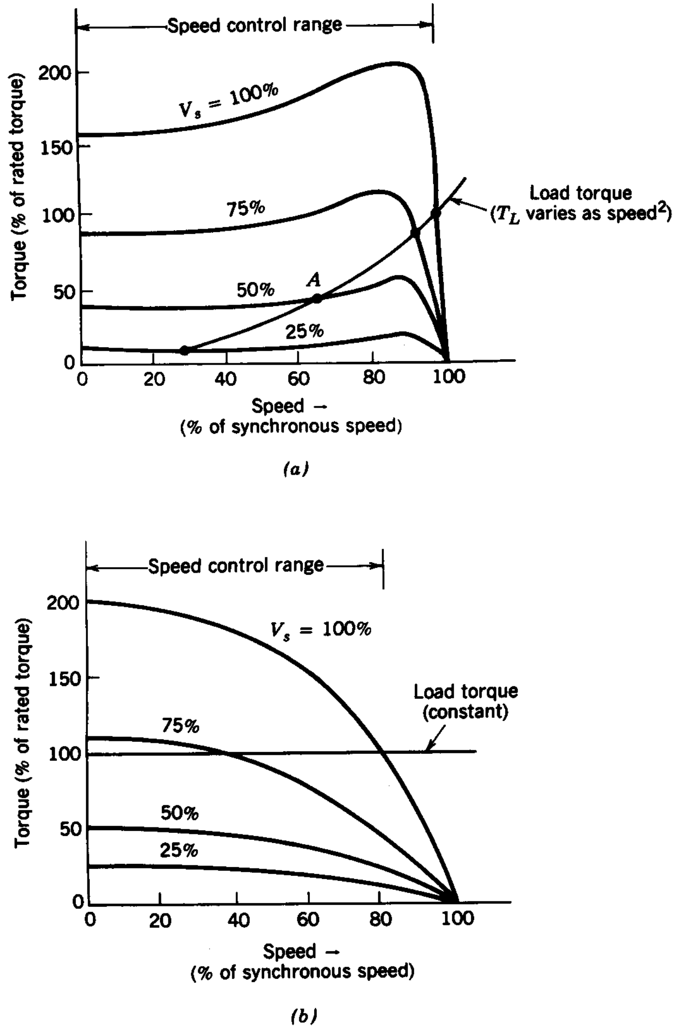

Figure 14-26 Speed control by stator voltage control: (*a*) motor with a low value of s_{rated}, fan-type load; (*b*) motor with a large s_{rated}, constant-torque load.

Controlling the Stator Voltage Magnitude

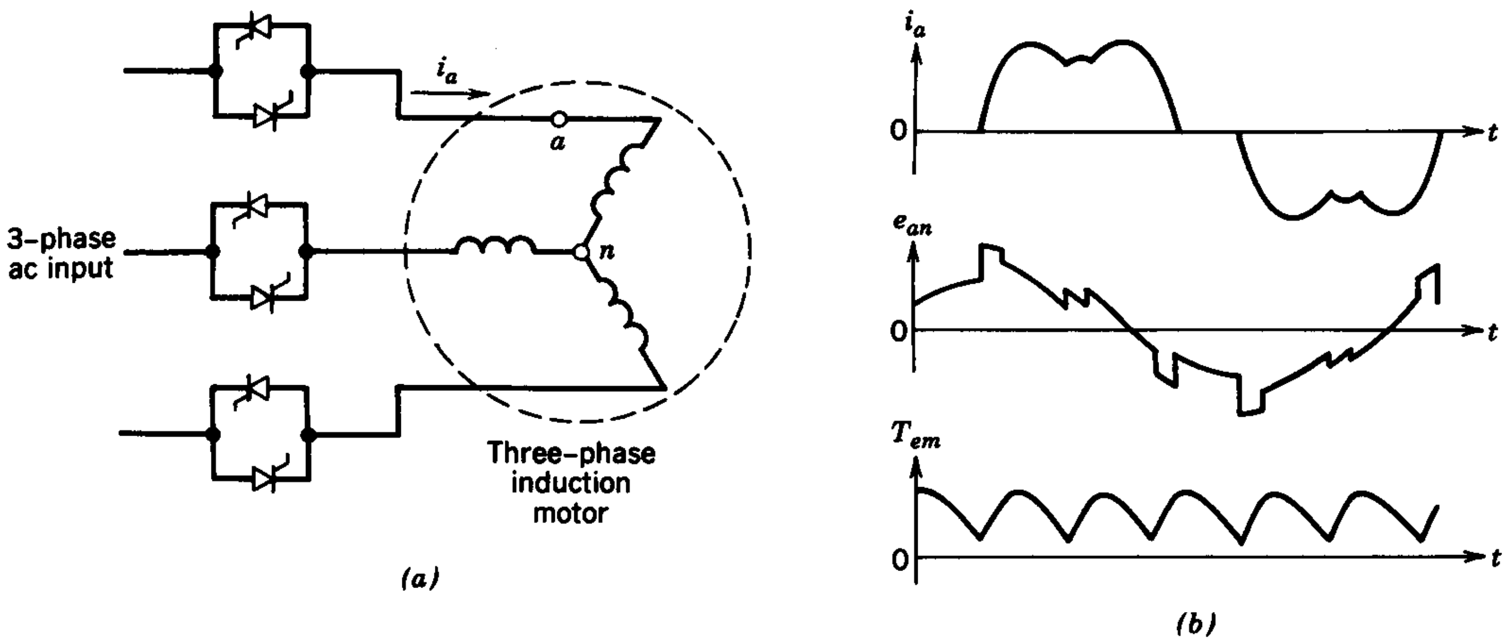

Figure 14-27 Stator voltage control: (*a*) circuit; (*b*) waveforms.

- Results in distorted current and torque pulsations

Torque-Speed Curves for Wound-Rotor Machines

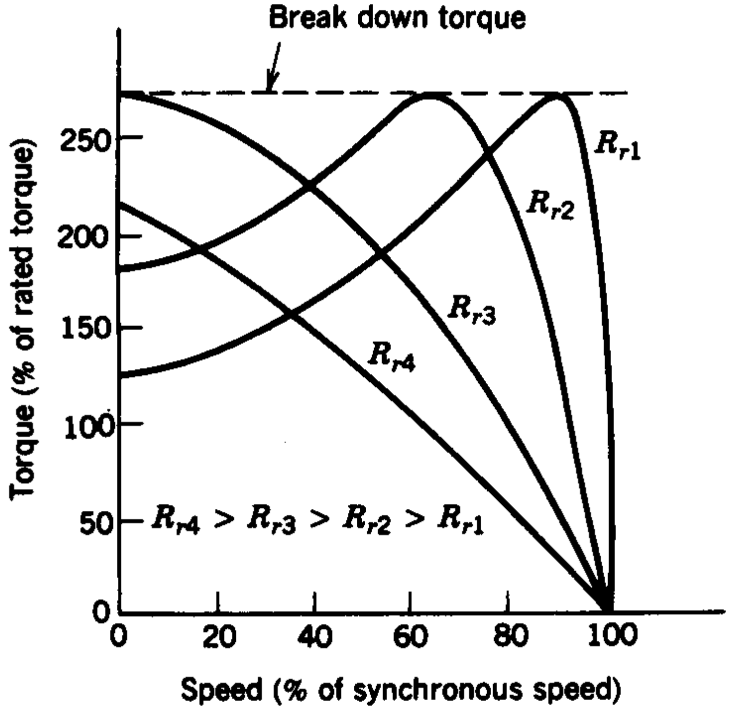

Figure 14-28 Torque–speed curves for a wound-rotor induction motor.

• Highly energy-inefficient unless using energy recovery schemes

Static Slip Recovery

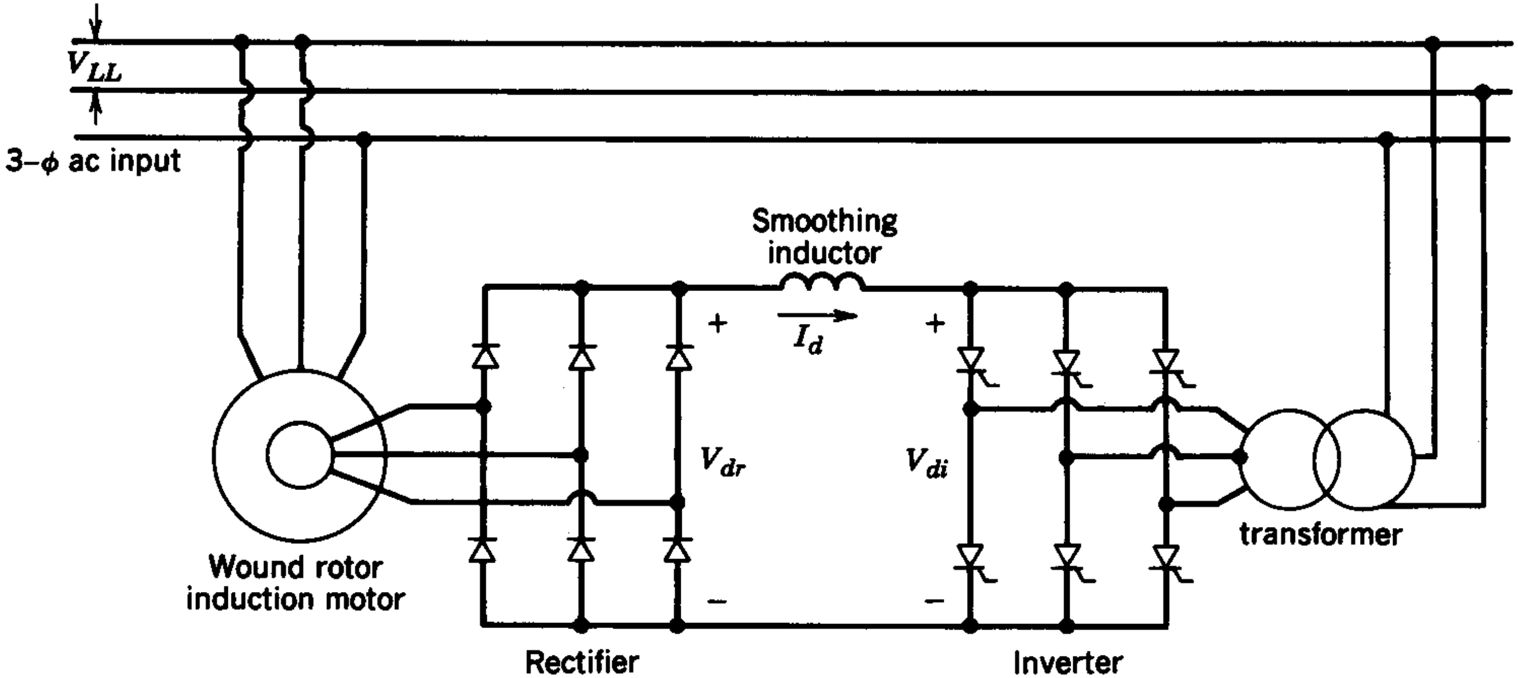

Figure 14-29 Static slip recovery.

• Applications in very large power ratings where the speed is to be adjusted over a very limited range