Power Electronics

Chap. 14

Induction Motor Drives

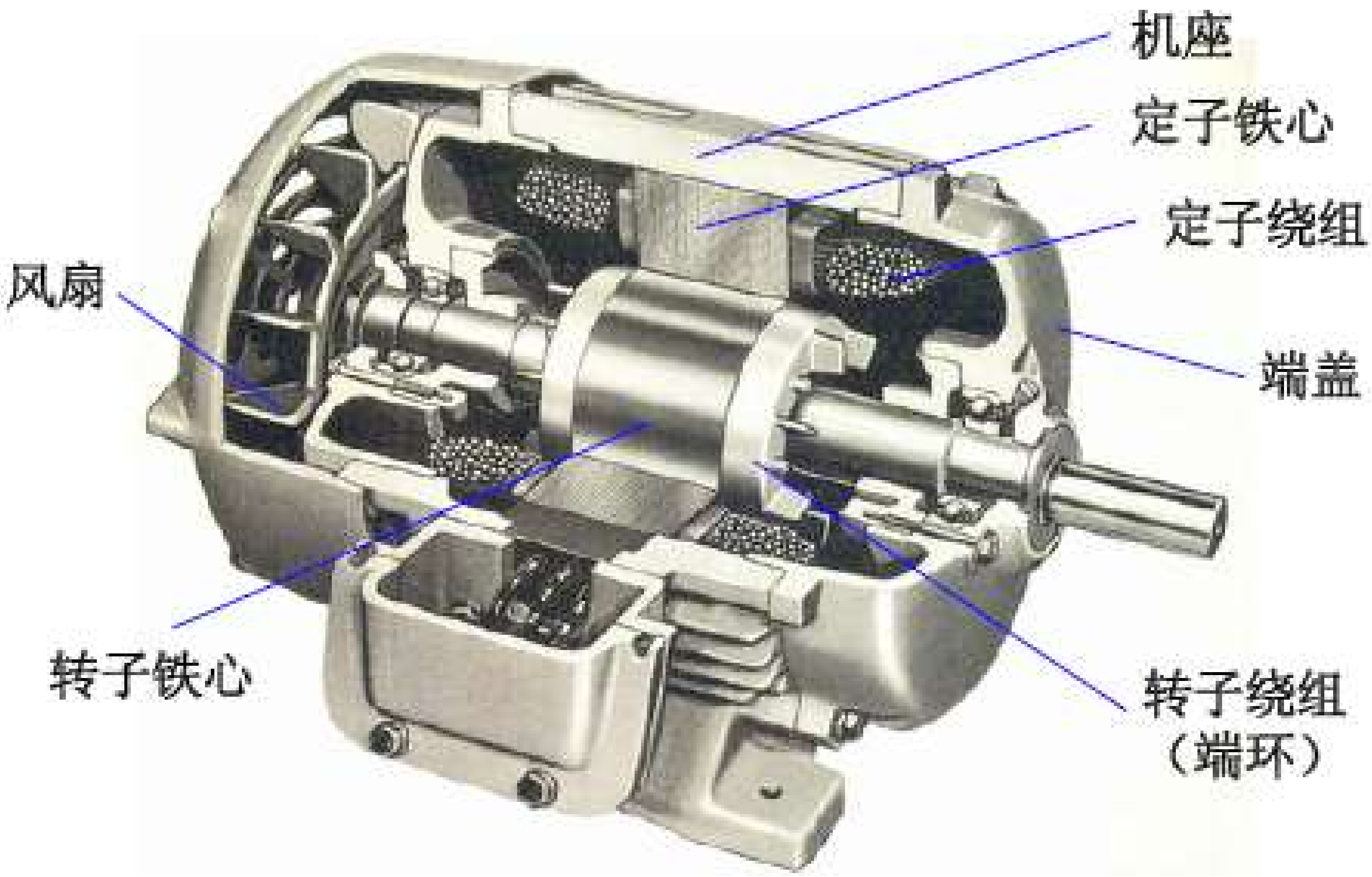
Outlines

- Introduction
- Basic Principles of Induction Motor Operation
- Induction Motor Characteristics at Rated Values
- Speed Control by Varying Stator Frequency and Voltage
- Impact of Nonsinusoidal Excitation on Induction Motors
- Variable-Frequency Converter Classifications
- Variable-Frequency PWM-VSI Drives
- Line-Frequency Variable-Voltage Drives

Chap.14 Induction Motor Drives

Basic Principles

• In a large majority of applications, induction motor drives incorporate a ***three-phase squirrel-cage motor***, since it is simple, low-cost and rugged.



Introduction

• Squirrel-cage induction motors are the workhorse of industry because of their *low cost* and *rugged construction*.

Induction Motor Drives

Adjustable-speed drives

Speed control

fans, compressors, pumps, blowers, etc.

Servo Drives

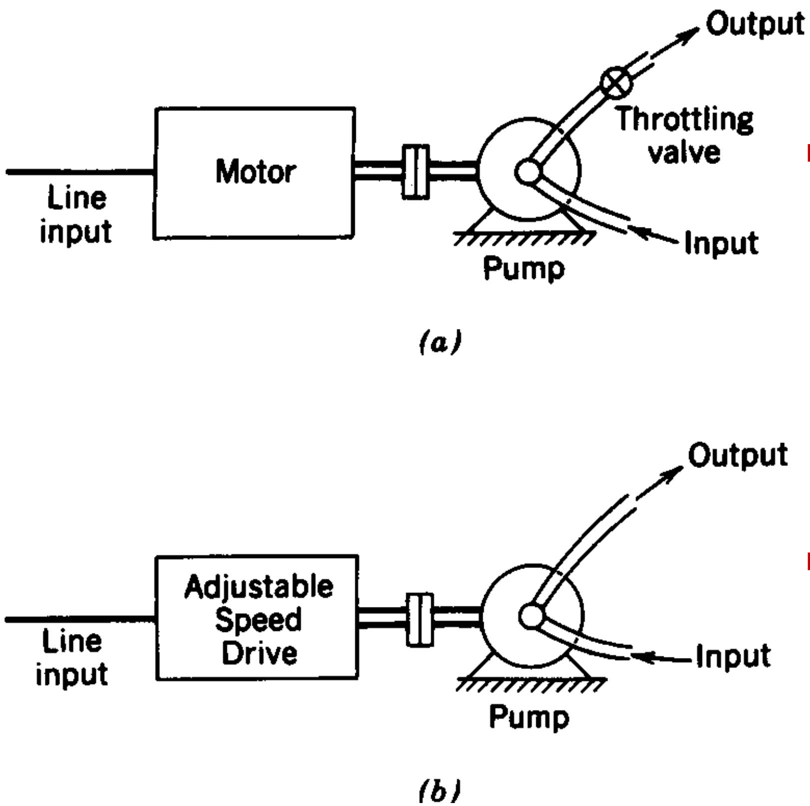
Sophisticated control

Computer peripherals, machine tools, robotics, etc.

Chap.14 Induction Motor Drives

Introduction

• In a centrifugal pump, $\text{Torque} \approx k_1(\text{speed})^2$, $\text{Power} \approx k_2(\text{speed})^3$



→ *Low **efficiency***

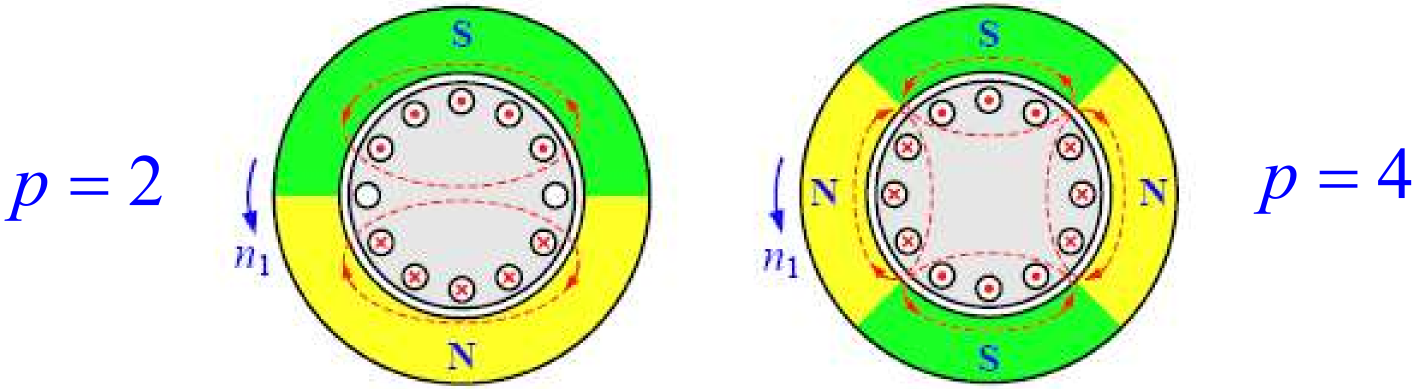
→ *High **efficiency***

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

• In comparison with a throttling valve to control the flow rate, the variable-speed-driven pump can result in significant energy conservation.

Basic Principles

Basic relationship between frequency & speed of IM



$$\omega_s = \frac{2\pi/(p/2)}{1/f} = \frac{2}{p}(2\pi f) = \frac{2}{p}\omega \quad \text{(rad/s)}$$

Mechanical synchronous angular speed (ω_s)

Electrical synchronous angular speed (ω)

$$n_s = 60 \times \frac{\omega_s}{2\pi} = \frac{120}{p} f$$

Motor synchronous speed (n_s) (r/min)

Number of Poles (p)

Stator frequency (f) (Hz)

Basic Principles

• The air gap flux ϕ_{ag} rotates at a synchronous speed. It induces a counter-emf (air gap voltage) E_{ag}.

$$N_s \phi_{ag} = L_m i_m \qquad\qquad E_{ag} = k_3 f \phi_{ag}$$

• The torque in an induction motor is produced by interaction of ϕ_{ag} and the rotor current. So there must be a relative motion between ϕ_{ag} and the rotor.

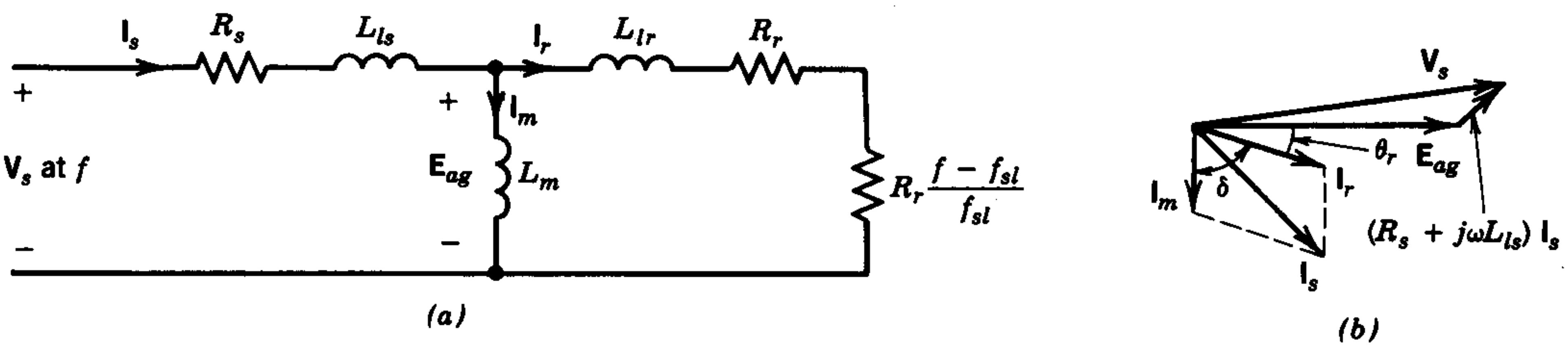


Figure 14-2 Per-phase representation: (*a*) equivalent circuit; (*b*) phasor diagram.

Basic Principles

• The relative motion is called "Slip".

$$\text{Slip} \quad s = \frac{\omega_s - \omega_r}{\omega_s}$$

Slip speed

$$\omega_{sl} = \omega_s - \omega_r = s\omega_s$$

Slip frequency

$$f_{sl} = \frac{\omega_{sl}}{\omega_s} f = sf$$

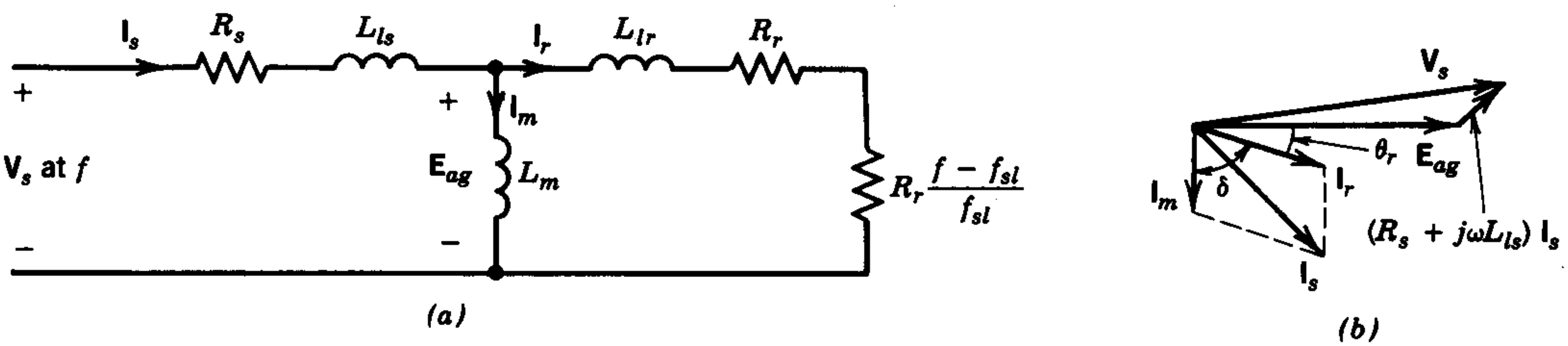


Figure 14-2 Per-phase representation: (*a*) equivalent circuit; (*b*) phasor diagram.

Basic Principles

- The induced rotor voltage results in the rotor currents at the slip frequency.

Induced rotor voltage $E_r = k_3 f_{sl} \phi_{ag}$

$$\mathbf{E}_r = R_r \mathbf{I_r} + j2\pi f_{sl} L_{lr} \mathbf{I_r}$$

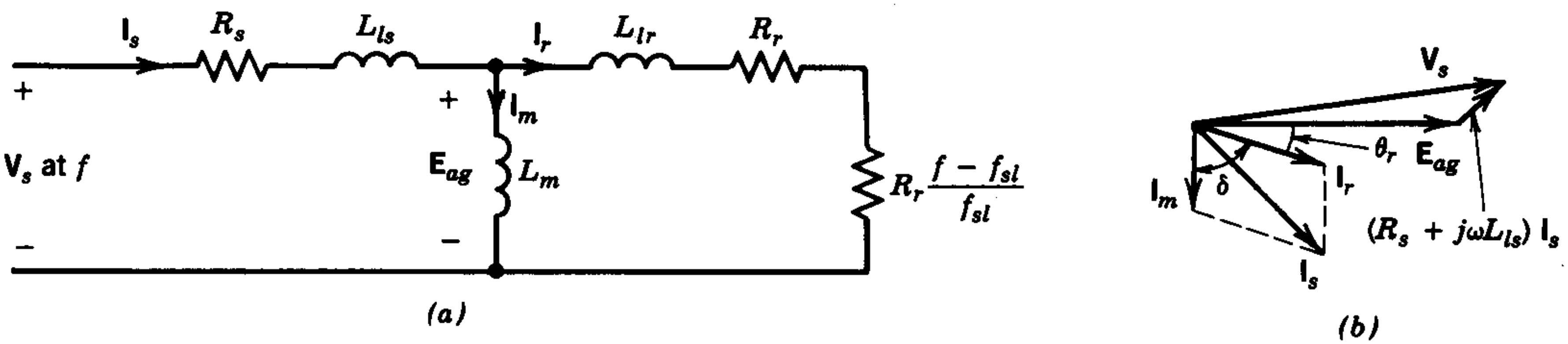


Figure 14-2 Per-phase representation: (*a*) equivalent circuit; (*b*) phasor diagram.

Basic Principles

- The relationships among the currents in induction motor

Magnetizing current

$$N_s\phi_{ag} = L_m i_m \Rightarrow I_m = k_8 \phi_{ag}$$

Rotor current

$$R_r \gg 2\pi f_{sl} L_{lr} \Rightarrow E_r \approx R_r I_r$$

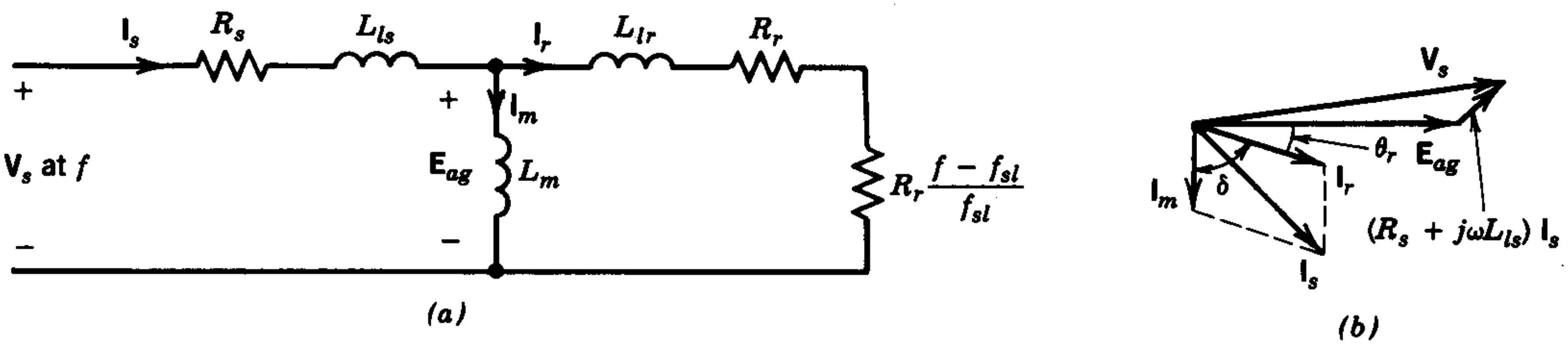


Figure 14-2 Per-phase representation: (a) equivalent circuit; (b) phasor diagram.

Basic Principles

- The relationships among the currents in induction motor

Magnetizing current

$$N_s\phi_{ag} = L_m i_m \Rightarrow I_m = k_8\phi_{ag}$$

Rotor current

$$E_r \approx R_r I_r$$

$$E_r = k_3 f_{sl}\phi_{ag} \Rightarrow I_r \approx k_5\phi_{ag} f_{sl}$$

$$\mathbf{I}_s = \mathbf{I}_m + \mathbf{I}_r \Rightarrow I_s \approx \sqrt{I_m^2 + I_r^2}$$

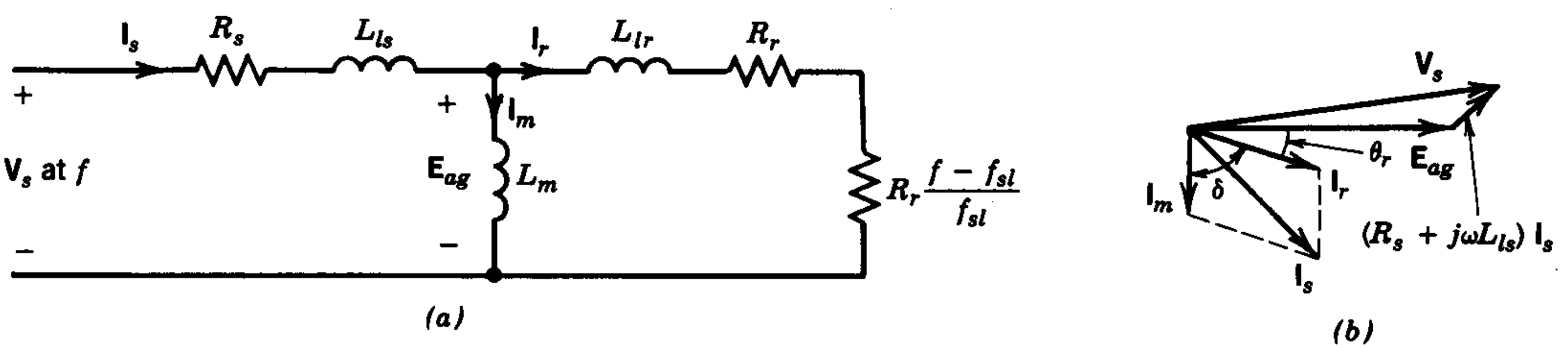


Figure 14-2 Per-phase representation: (*a*) equivalent circuit; (*b*) phasor diagram.

Basic Principles

- The relationship of power in induction motor

Air gap power

$$P_{ag} = 3\frac{f}{f_{sl}}R_r I_r^2$$

Power loss in rotor

$$P_r = 3R_r I_r^2$$

Electromechanical output power

$$P_{em} = P_{ag} - P_r = 3R_r \frac{f - f_{sl}}{f_{sl}} I_r^2$$

$$\%P_r = \frac{P_r}{P_{em}} = \frac{f_{sl}}{f - f_{sl}}$$

Chap.14 Induction Motor Drives

Basic Principles

Electromagnetic torque

$$T_{em} = \frac{P_{em}}{\omega_r} = \frac{P_{ag}}{\omega_s}$$

- Under the following condition,

$$\underbrace{R_r >> 2\pi f_{sl} L_{lr} \qquad \theta_r \approx 0^\circ \qquad \delta \approx 90^\circ}$$

$$T_{em} = k_4 \phi_{ag} I_r \sin\delta \approx k_4 \phi_{ag} I_r \approx k_6 \phi_{ag}^2 f_{sl}$$

$$I_r \approx k_5 \phi_{ag} f_{sl}$$

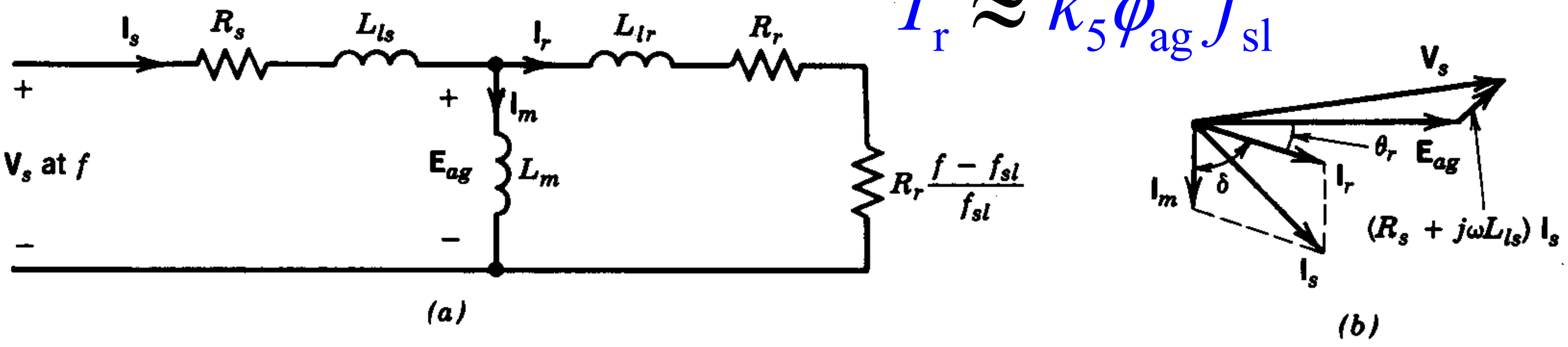


Figure 14-2 Per-phase representation: (*a*) equivalent circuit; (*b*) phasor diagram.

Basic Principles

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)
$I_s \simeq$	$\sqrt{I_m^2 + I_r^2}$

$$V_s \approx E_{ag}$$

$$\approx \frac{f}{f_{sl}} R_r I_r \quad (R_r >> 2\pi f_{sl} L_{lr})$$

$$I_r \approx k_5 \phi_{ag} f_{sl}$$

$$\approx k_3 \phi_{ag} f$$

Stator frequency

V/f constant control

Characteristics at Rated Values

- In the commonly used induction motors, f_{sl} is kept small, hence, the dashed portions of the torque are not used due to high power loss.

Dashed portions are not used

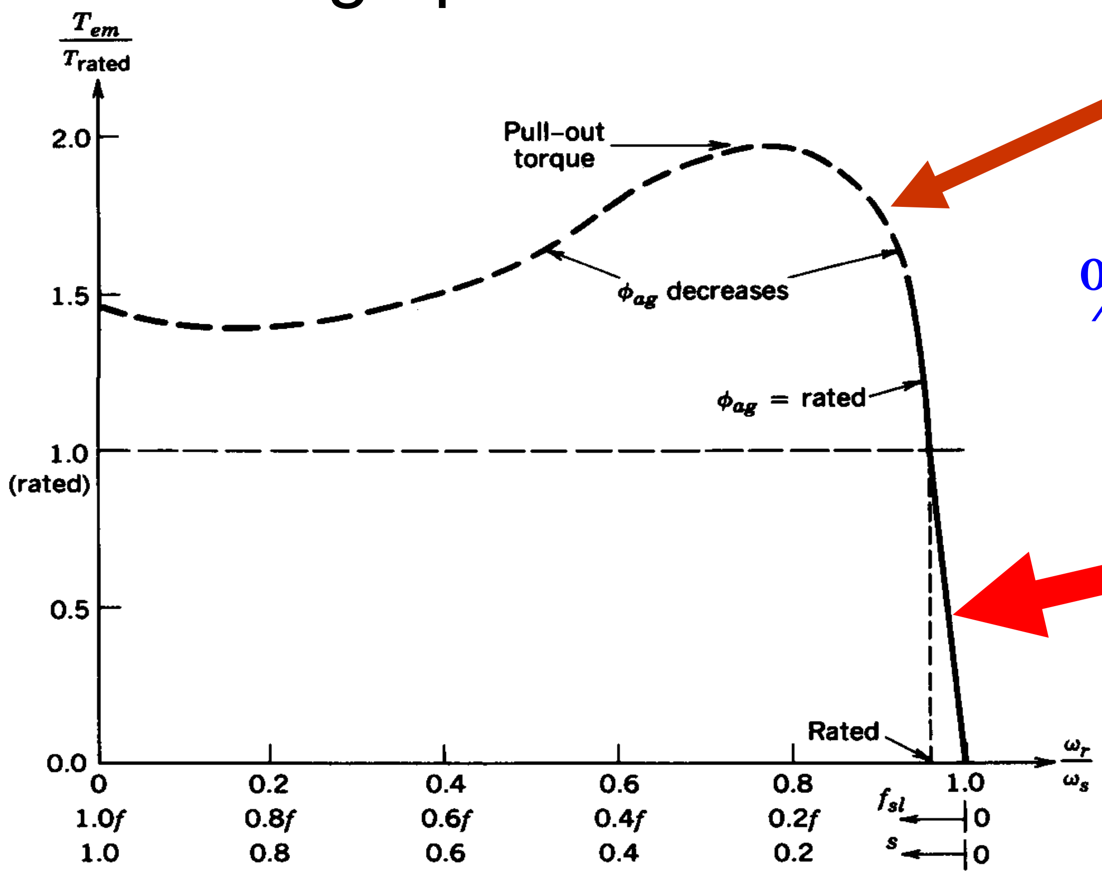


Figure 14-3 A typical torque–speed characteristic; V_s and f are constant at their rated values.

$$\%P_r = \frac{P_r}{P_{em}} = \frac{f_{sl}}{f - f_{sl}}$$

Linear portions are used

Characteristics at Rated Values

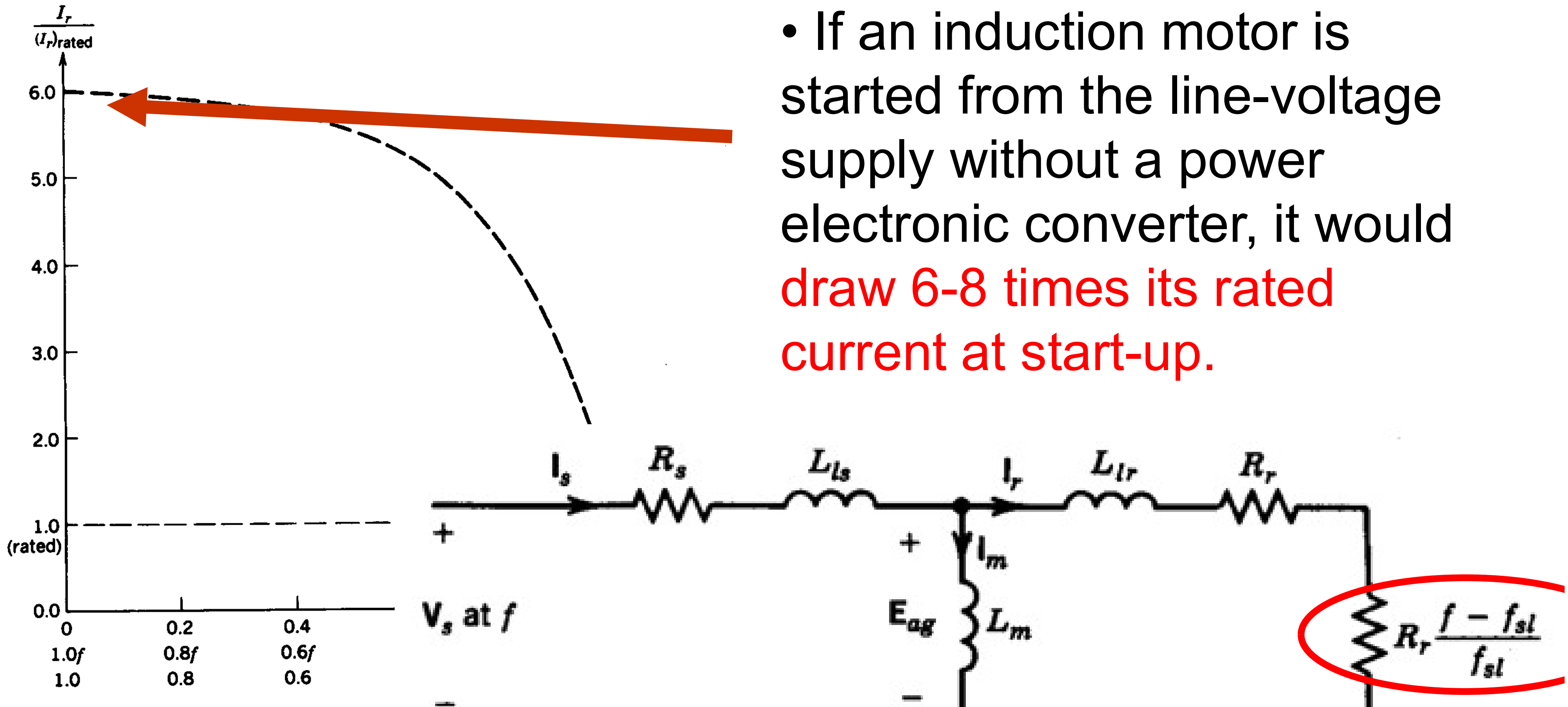


Figure 14-4 Plot of I_r versus f_{sl}; V_s a
values.

- If an induction motor is started from the line-voltage supply without a power electronic converter, it would draw 6-8 times its rated current at start-up.

Characteristics at Rated Values

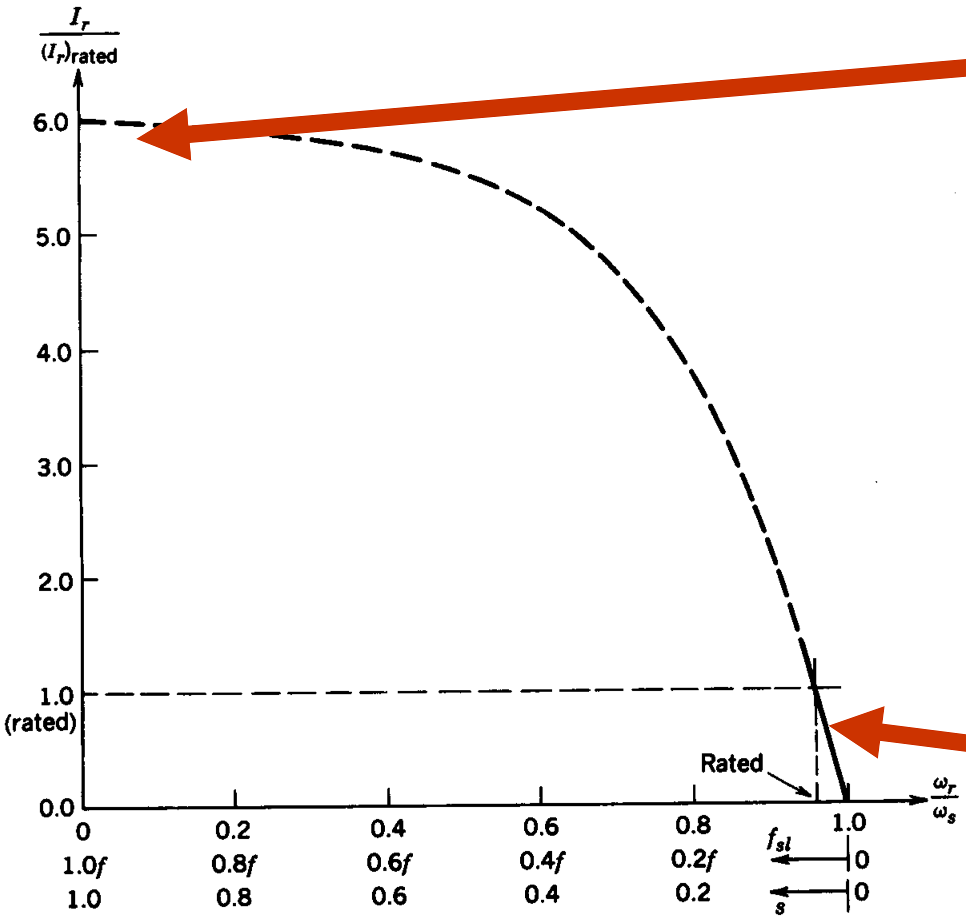


Figure 14-4 Plot of I_r versus f_{sl}; V_s and f are constant at their rated values.

- If an induction motor is started from the line-voltage supply without a power electronic converter, it would draw 6-8 times its rated current at start-up.

- In the commonly used induction motors, f_{sl} is kept small, hence, the dashed portions of the torque are not used.

Characteristics at Rated Values

- Available acceleration torque $T_{\mathrm{em}} - T_{\mathrm{load}}$ for the motor to accelerate from standstill.
- The intersection determines the steady-state point of operation.

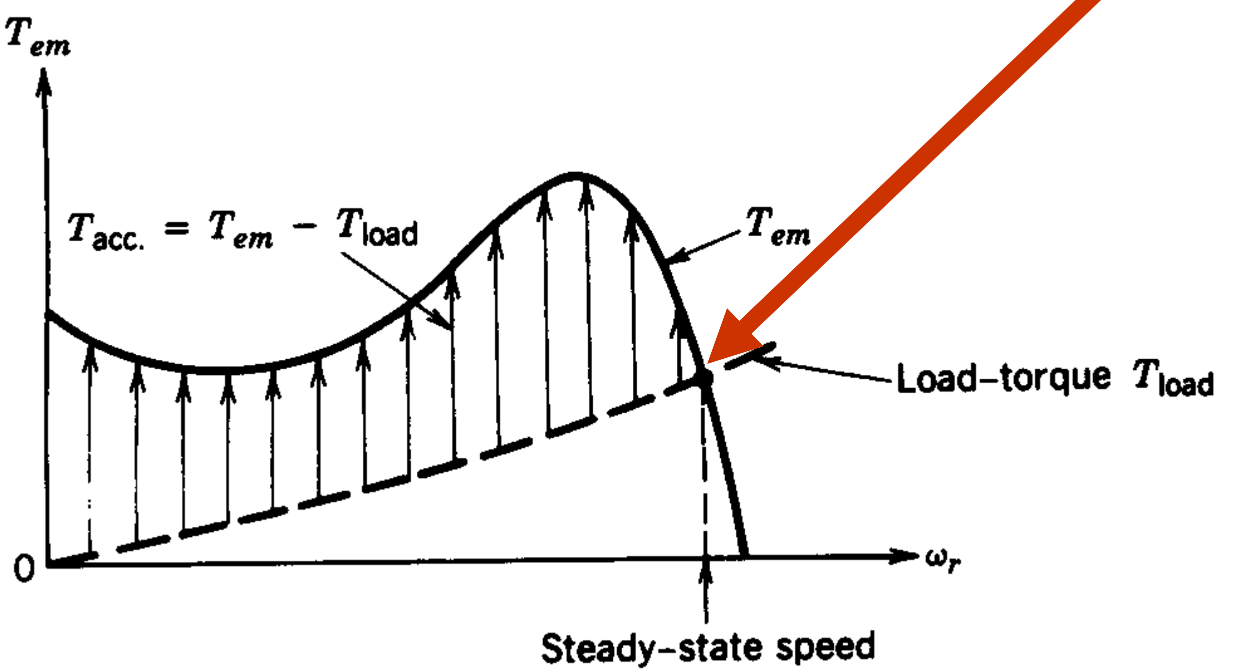


Figure 14-5 Motor start-up; V_s and f are constant at their rated values.

Speed Control by Varying Stator Frequency and Voltage (VVVF)

14.4.1 Torque-Speed Characteristics

- For small values of f_{sl}, keeping ϕ_{ag} constant results in a linear relationship between T_{em} and f_{sl}.

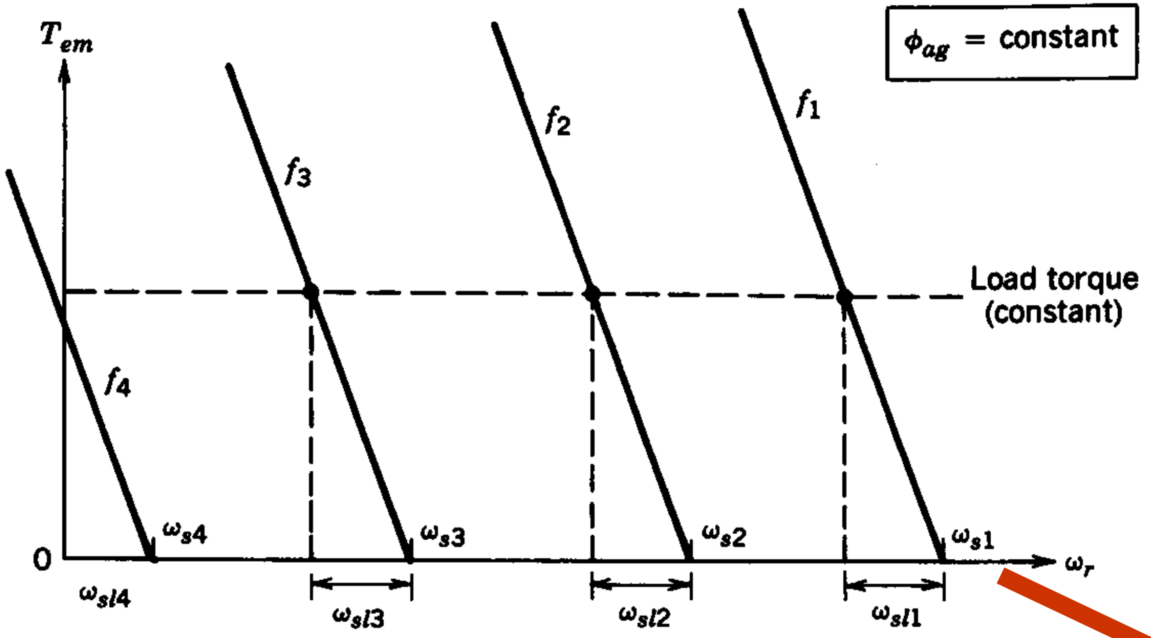


Figure 14-6 Torque–speed characteristics at small slip with a constant ϕ_{ag}; constant load torque.

$$T_{em} \approx k_6 \phi_{ag}^2 f_{sl}$$

$$T_{em} \approx k_9 f_{sl}$$

$$\omega_{sl} = \frac{f_{sl}}{f_s}\omega_s = \frac{4\pi}{p} f_{sl}$$

$$T_{em} \approx k_{10}\omega_{sl}$$

$$\omega_{sl1} = \omega_{sl2} = \omega_{sl3} = \omega_{sl4}$$

Speed Control by Varying Stator Frequency and Voltage (VVVF)

- In many loads such as the centrifugal pumps, compressors, and fans, the load torque varies by the square of the speed.

$$T_{load} \approx k_1 (\text{speed})^2$$

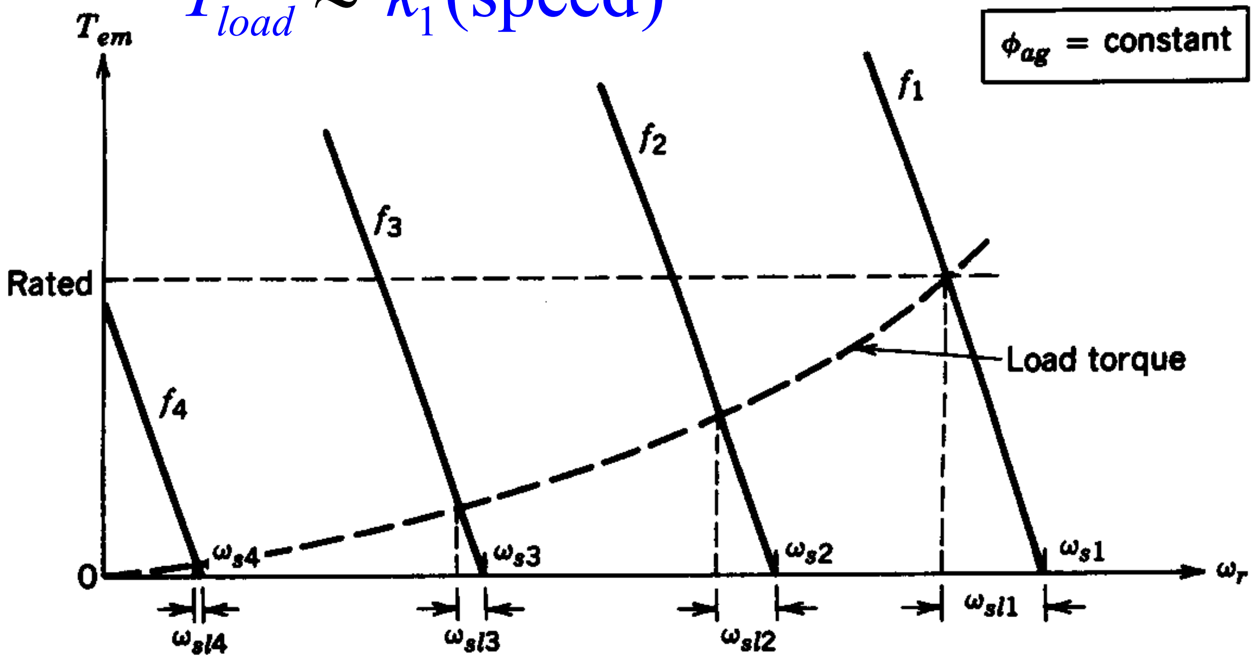


Figure 14-7 Centrifugal load torque; torque varies as the speed squared.

$$T_{em} \approx k_{10}\omega_{sl} \qquad \omega_{sl1} > \omega_{sl2} > \omega_{sl3} > \omega_{sl4}$$

Speed Control by Varying Stator Frequency and Voltage (VVVF)

Example 14-1

• A four-pole, 1hp, 380V motor is supplying its rated power to a centrifugal load at a 50-Hz. Its rated speed is 1425 rpm.

• Calculate its speed, slip frequency, and slip when it is supplied by a 228V, 30Hz source.

Solution

Calculation at rated condition $\longrightarrow$ Calculation at 228V/30Hz

Keeping V_s / f *constant,*

$$T_{em} \approx k_9 f_{sl} \qquad\qquad T_{load} \approx k_1 (\text{speed})^2$$

主观题 10分 设置

Calculate the rated slip frequency.

作答

Speed Control by Varying Stator Frequency and Voltage (VVVF)

Solution

$$n_s = 1500\text{rpm} \quad n_s = 1425\text{rpm}$$

$$s_{\text{rated}} = (1500 - 1425)/1500 = 0.05$$

$$f_{sl,\text{rated}} = 0.05 \times 50 = 2.5\text{Hz} \qquad T_{\text{em}} \approx k_9 f_{\text{sl}}$$

$$T_{\text{em}} = 0.6^2 \times T_{\text{rated}} = 0.36 T_{\text{rated}} \quad T_{load} \approx k_1 (\text{speed})^2$$

$$f_{sl} = 0.36 f_{sl,\text{rated}} = 0.9\text{Hz}$$

$$s = 0.9/30 = 0.03 \qquad n_r = (1 - s) \times 900 = 873\text{rpm}$$

Results

$$n_r = 873 \quad \text{rpm} \qquad s = 3\% \qquad f_{\text{sl}} = 0.9 \quad \text{Hz}$$

Speed Control by Varying Stator Frequency and Voltage (VVVF)

- For a inverter-driven induction motor, it is important to keep the current draw from becoming large during start-up.

$$T_{em} \approx k_4 \phi_{ag} I_r \qquad I_r \approx k_5 \phi_{ag} f_{sl}$$

- For a constant ϕ_{ag},

$$I_r \approx k_{11} f_{sl}$$

$$T_{em} \approx k_9 f_{sl}$$

- By VVVF control,

$$f_{start} \approx \frac{T_{start}}{T_{rated}} (f_{sl})_{rated}$$

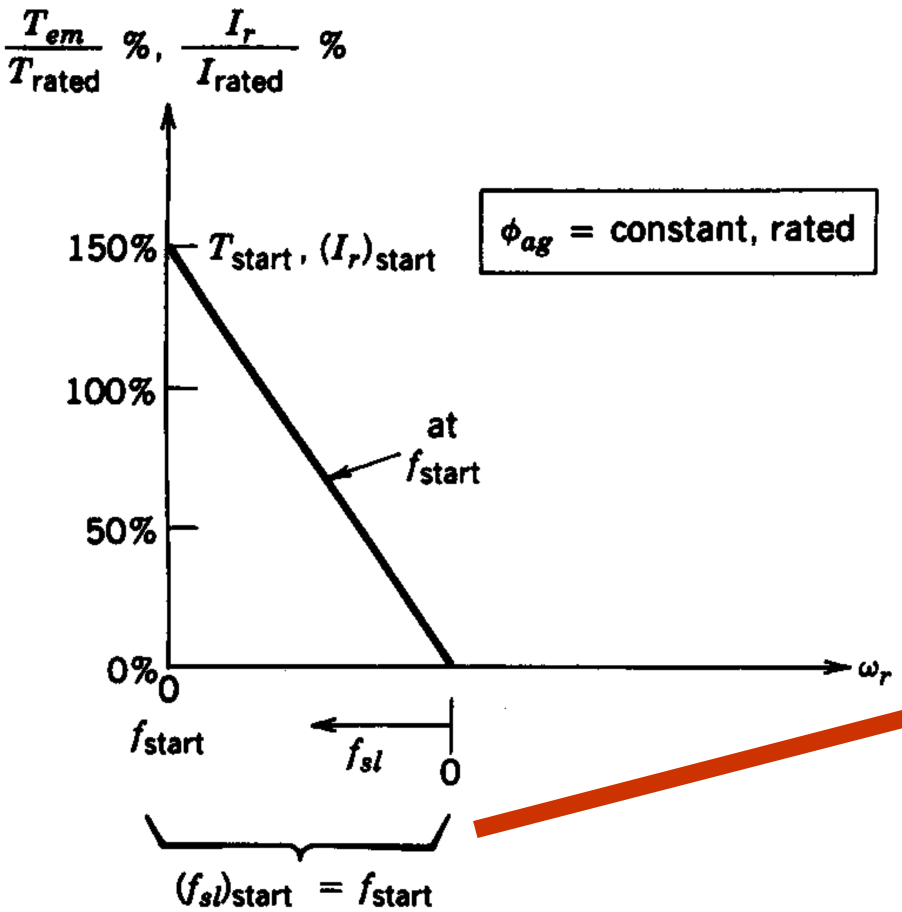


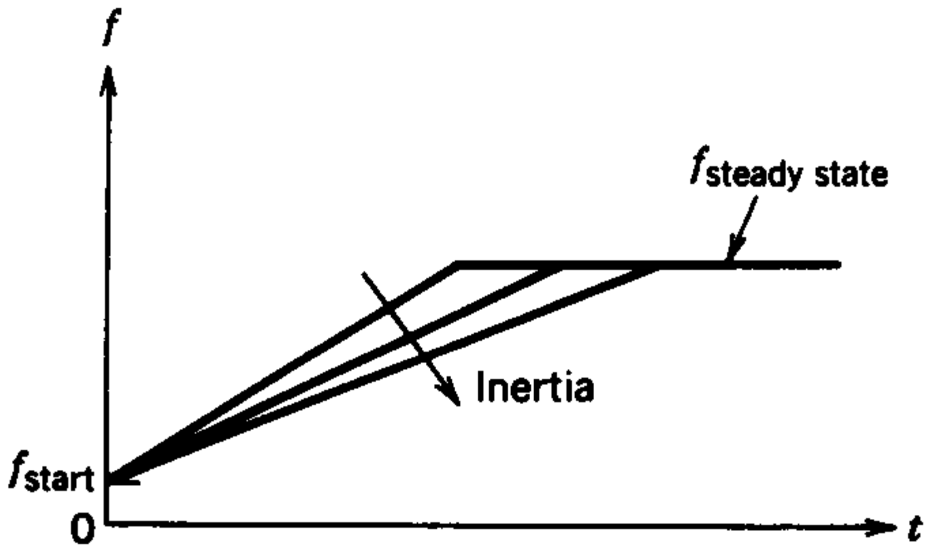
Figure 14-8 Frequency at start-up.

Speed Control by Varying Stator Frequency and Voltage (VVVF)

14.4.2 Start-up Considerations

• In practice, the stator frequency f is increasing continuously at a preset rate, which does not let the current exceed a specified limit until the final desired speed has been achieved.

• This rate is decreased for higher inertia loads to allow the rotor speed to catch up.



$$T - T_{\text{load}} = J\frac{d\omega}{dt}$$

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

Speed Control by Varying Stator Frequency and Voltage (VVVF)

14.4.3 Voltage Boost Required at Low Frequencies

- In induction motors of normal design, $2\pi f L_{lr} << R_r(f/f_{sl})$.

Hence, I_r will be in phase with E_{ag}.

$$\mathbf{I}_s = \mathbf{I}_r + \mathbf{I}_m = I_r - jI_m$$

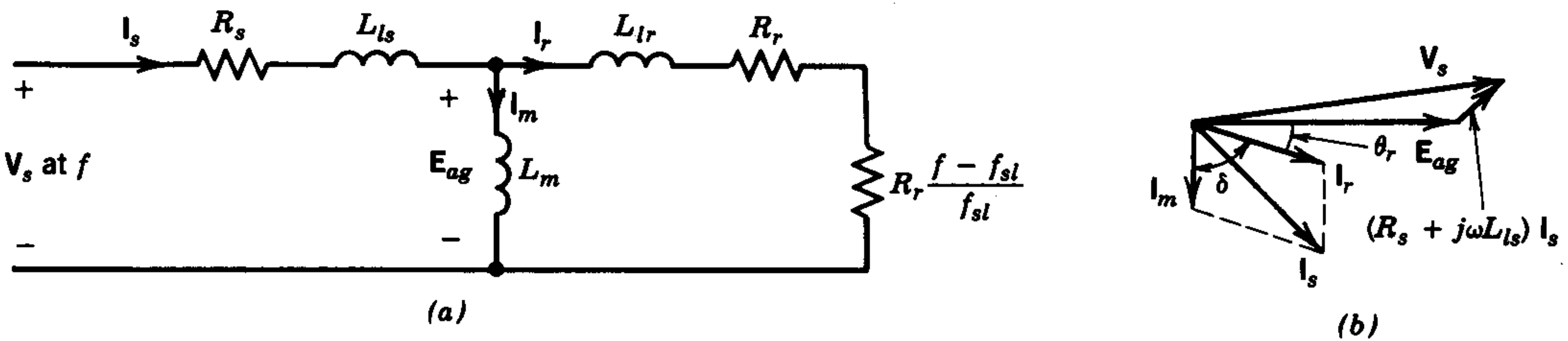


Figure 14-2 Per-phase representation: (*a*) equivalent circuit; (*b*) phasor diagram.

Speed Control by Varying Stator Frequency and Voltage (VVVF)

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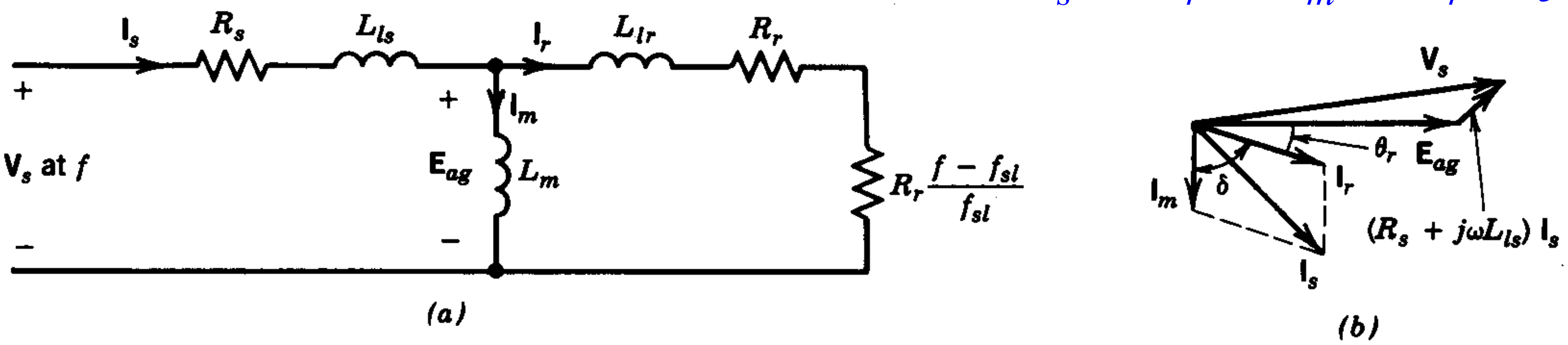


Figure 14-2 Per-phase representation: (*a*) equivalent circuit; (*b*) phasor diagram.

$$\mathbf{V}_s = \mathbf{E}_{\mathbf{ag}} + (R_s + j2\pi fL_{ls})\mathbf{I}_s$$

$$\Downarrow$$

$$\mathbf{V}_s = [E_{\mathbf{ag}} + (2\pi fL_{ls})I_m + R_s I_r] + j[(2\pi fL_{ls})I_r - R_s I_m]$$

Speed Control by Varying Stator Frequency and Voltage (VVVF)

$$\mathbf{V}_s = [E_{\mathbf{ag}} + (2\pi f L_{\mathbf{ls}}) I_{\mathbf{m}} + R_{\mathbf{s}} I_{\mathbf{r}}] + j[(2\pi f L_{\mathbf{ls}}) I_{\mathbf{r}} - R_{\mathbf{s}} I_{\mathbf{m}}]$$

Its influence on the magnitude of $V_{\mathbf{s}}$ *can be neglected.*

$$V_s \approx E_{\mathbf{ag}} + (2\pi f L_{ls}) I_m + R_s I_r$$

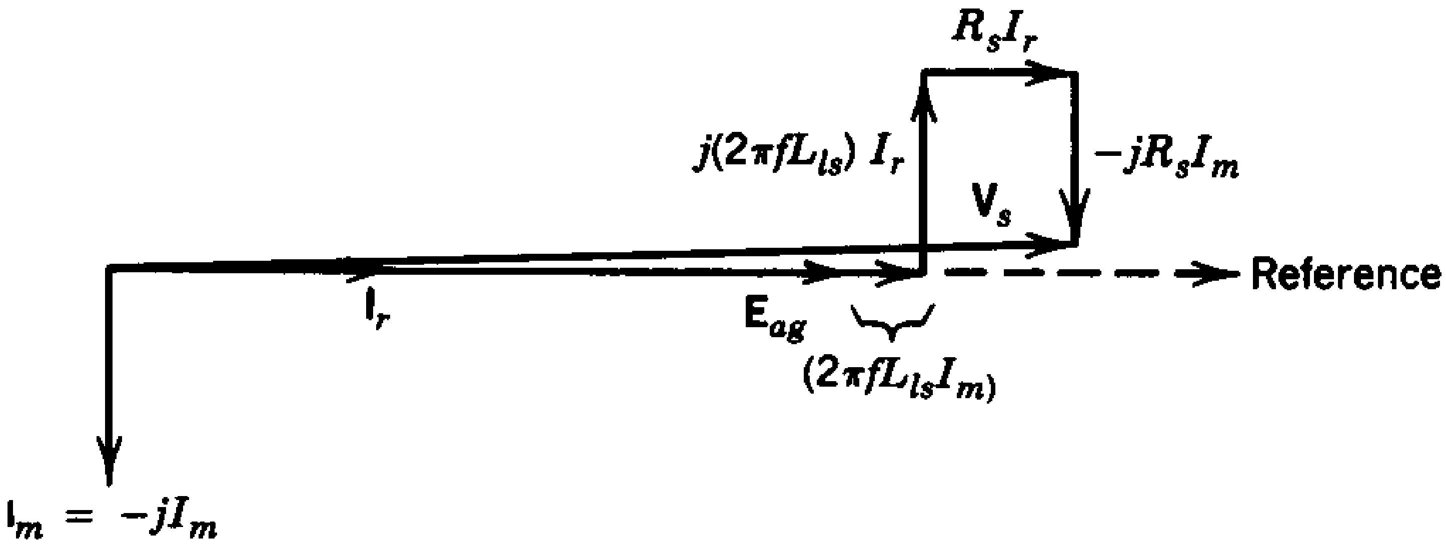


Figure 14-10 Phasor diagram at a small value of f_{sl}.

Speed Control by Varying Stator Frequency and Voltage (VVVF)

$$V_s \approx E_{ag} + (2\pi f L_{ls}) I_m + R_s I_r$$

$$E_{ag} = k_3 f \phi_{ag} \qquad I_m = k_8 \phi_{ag}$$

If ϕ_{ag} *is kept constant.*

$$V_s \approx k_{12} f + R_s I_r$$

proportional to T_{em}

$$T_{em} \approx k_4 \phi_{ag} I_r$$

$$V_{s(rated)} \approx k_{12} f_{rated} + R_s I_{r(rated)}$$

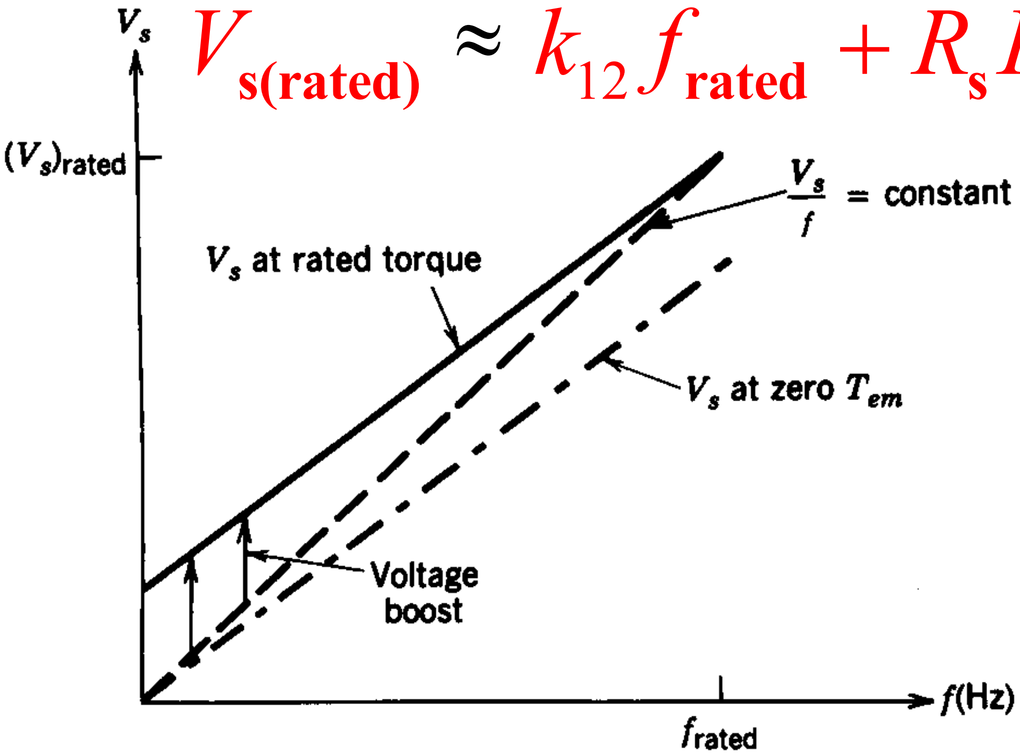
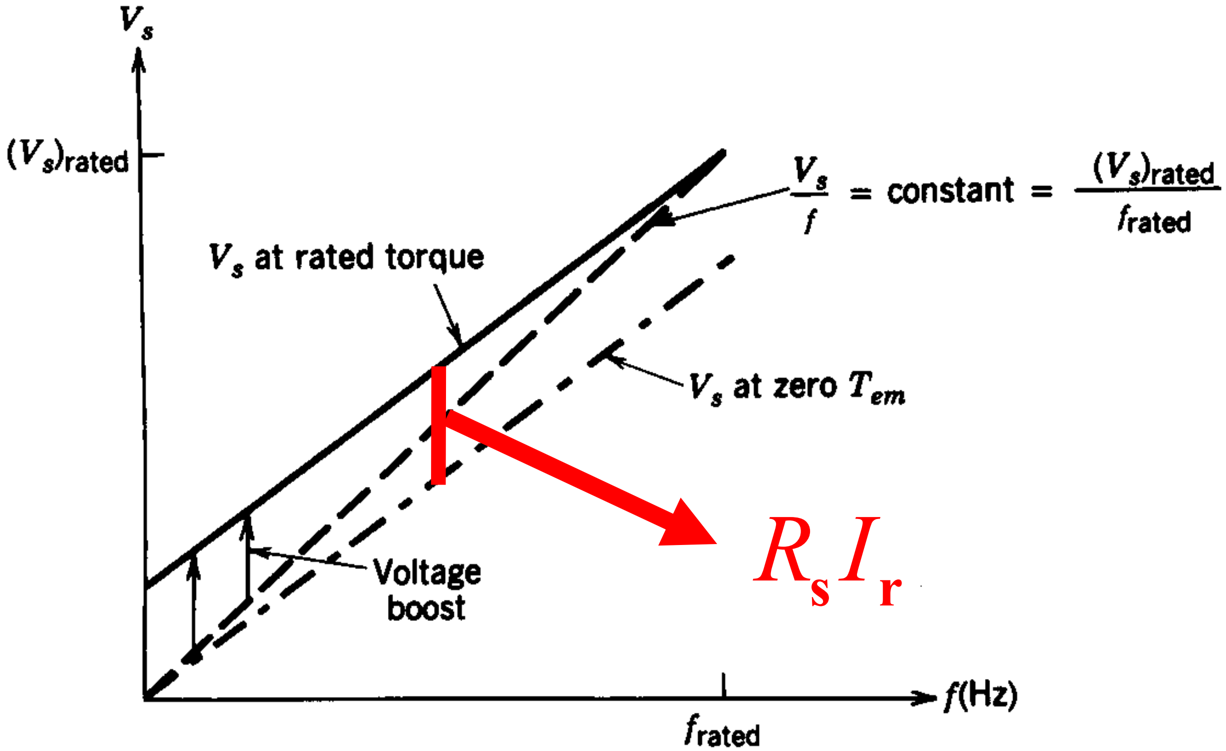


Figure 14-11 Voltage boost required to keep ϕ_{ag} constant.

Speed Control by Varying Stator Frequency and Voltage (VVVF)

- To keep ϕ_{ag} constant, a much higher percentage voltage boost is required at low operating frequencies due to the voltage drop across R_s.



$$V_s \approx k_{12} f + R_s I_r$$

proportional to T_{em}

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

Speed Control by Frequency and V

14.4.4 Induction Motor Capability

- Most induction motors can be operated up to twice the rated speed without any mechanical problems.

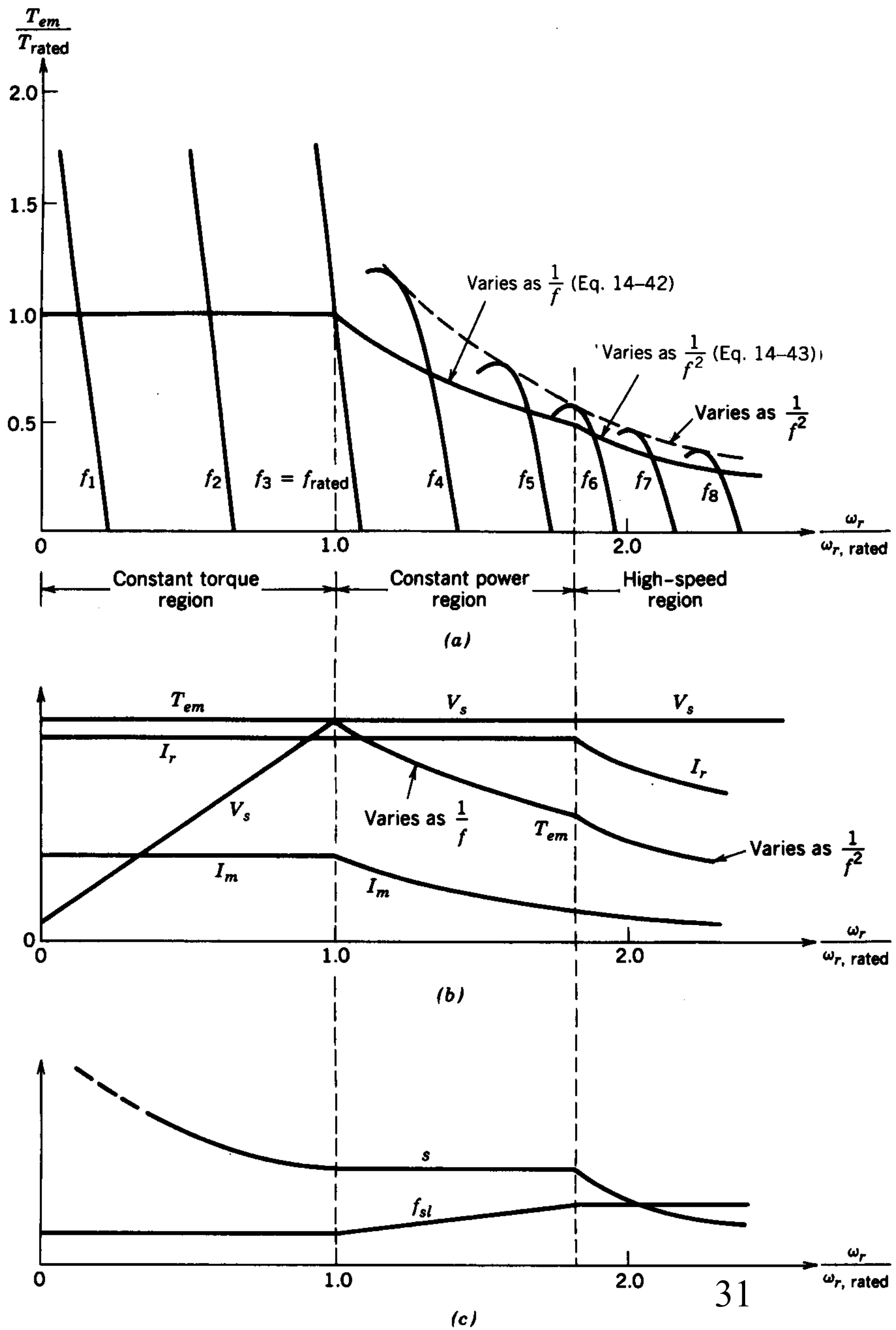


Figure 14-12 Induction motor characteristics and capabilities.

Speed Control by Frequency and V

- Most induction motors can be operated up to twice the rated speed without any mechanical problems.

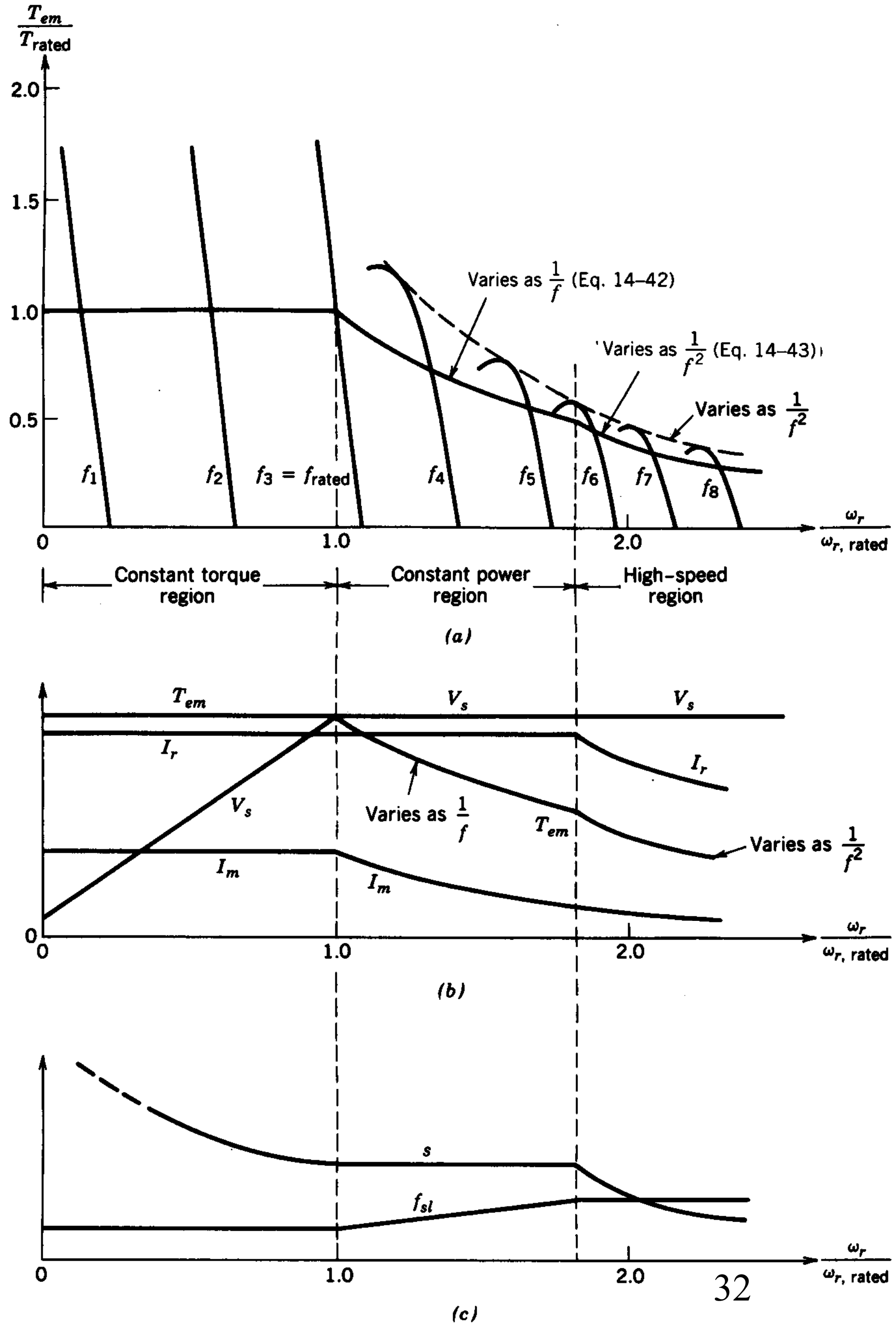


Figure 14-12 Induction motor characteristics and capabilities.

Below the rated speed:
Constant-Torque Region

Beyond the rated speed:
Constant-Power Region

High speed operation:
Constant- f_{sl} Region

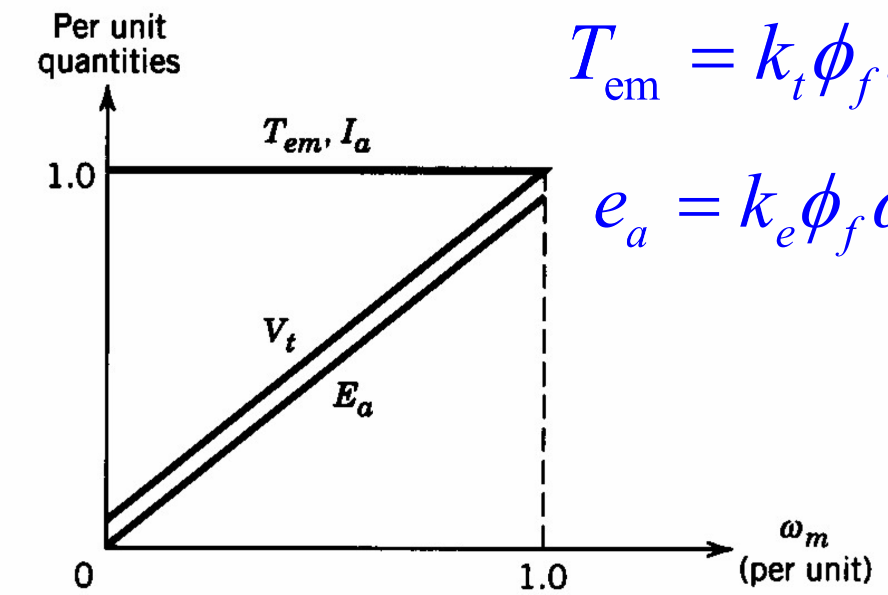
设置

Please draw the torque-speed capabilities of a permanent-magnet dc motor and a dc motor with a separately excited fielding winding.

作答

Speed Control by Varying Stator Frequency and Voltage (VVVF)

Torque-speed capability



$$T_{\text{em}} = k_t \phi_f i_a$$

$$e_a = k_e \phi_f \omega_m$$

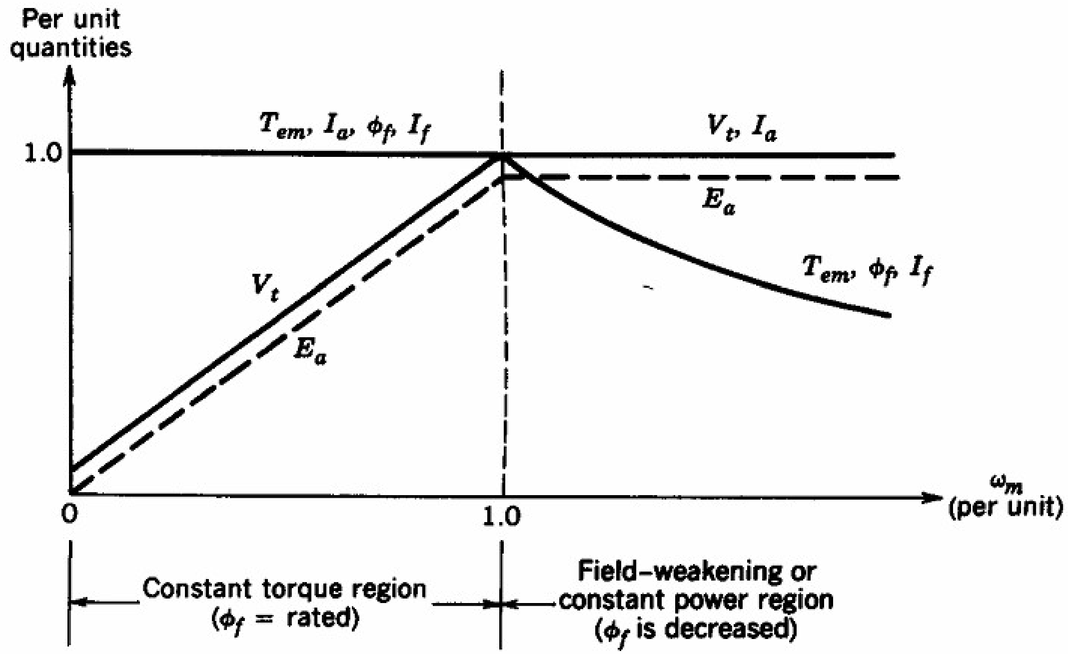


Figure 13-5 Separately excited dc motor: (*a*) equivalent circuit; (*b*) continuous torque–speed capability.

Permanent-magnet dc motor

DC motor with a separately excited fielding winding

Speed Control by Frequency and V

Below the rated speed: Constant-Torque Region

$$T_{em} \approx k_6 \phi_{ag}^2 f_{sl}$$

- If ϕ_{ag} is maintained constant, the motor can deliver its rated torque by drawing its rated current at a constant f_{sl}.

$$E_{ag} = k_3 f \phi_{ag}$$

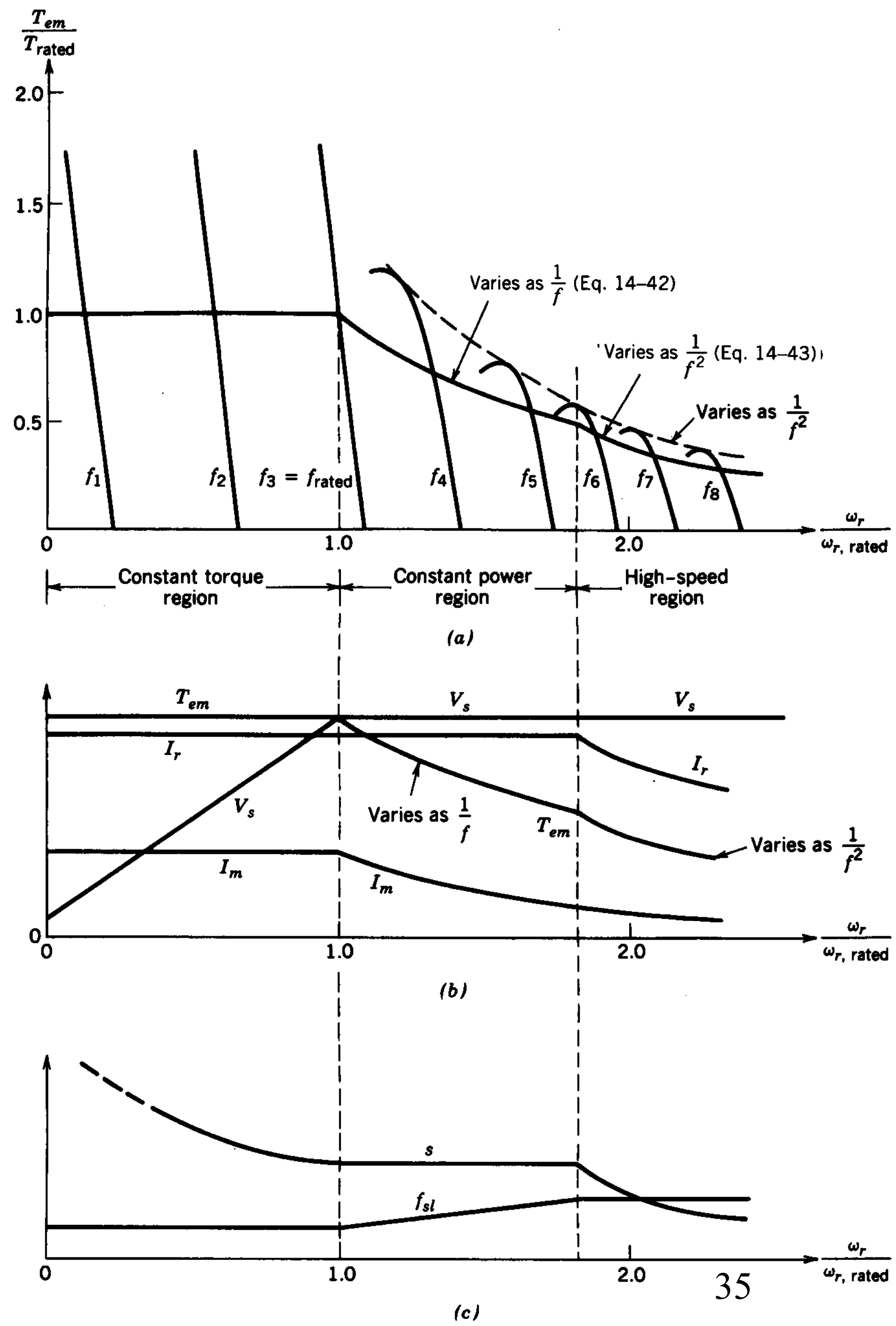


Figure 14-12 Induction motor characteristics and capabilities.

—— Speed Control by Frequency and V

Beyond the rated speed:

Constant-Power Region

$$E_{ag} = k_3 f \phi_{ag}$$

$$V_s = \text{constant} \quad f\uparrow \quad \phi_{ag}\downarrow$$

$$T_{em} \approx k_6 \phi_{ag}^2 f_{sl}$$

$$V_s \approx k_3 \phi_{ag} f \qquad \omega_{sl} = \frac{4\pi}{p} f_{sl}$$

$$T_{em} \approx \frac{k_{13}}{f^2}\omega_{sl}$$

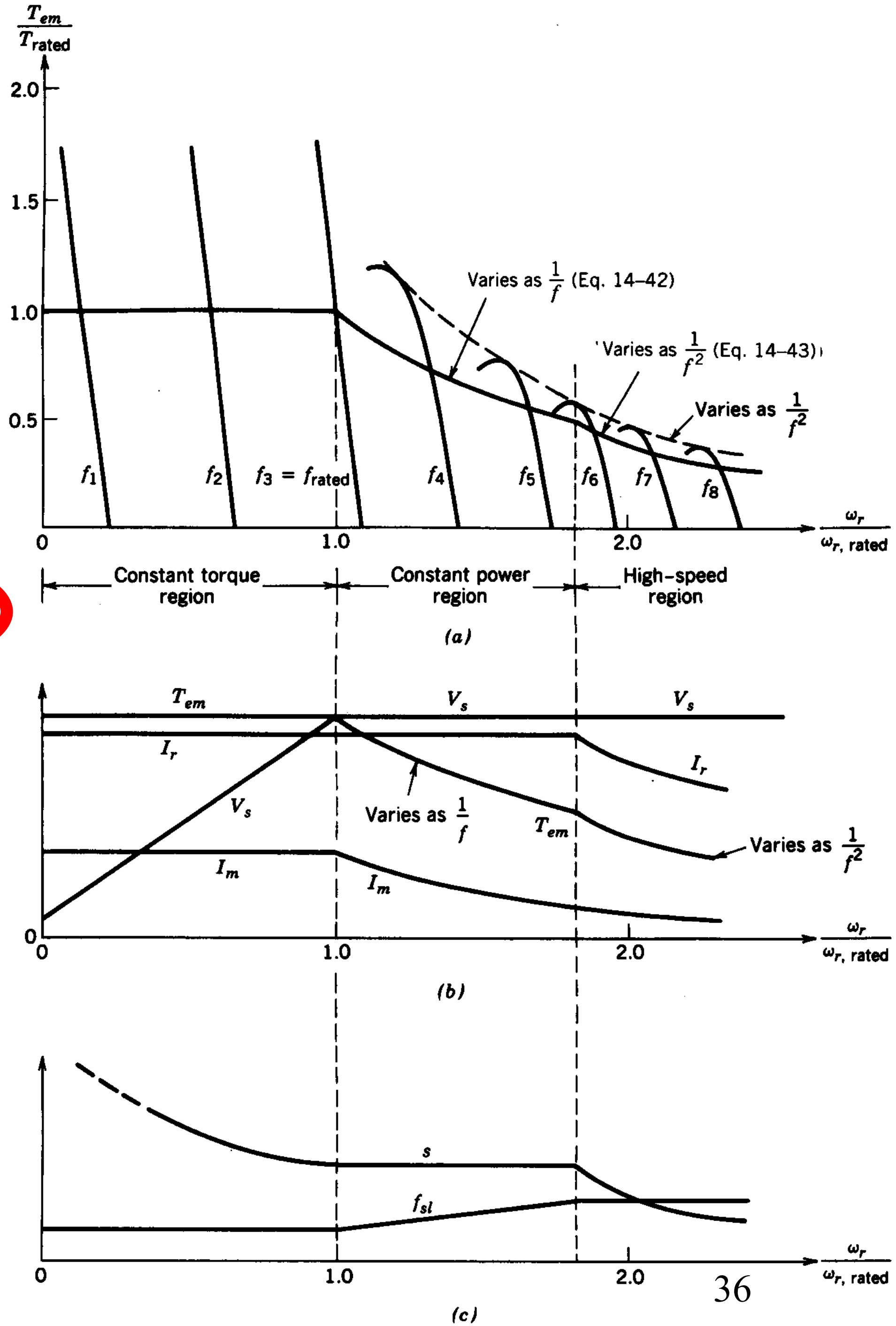


Figure 14-12 Induction motor characteristics and capabilities.

—— Speed Control by Varying Frequency and Voltage

- Slip is constant.

$$T_{em} \approx \frac{k_{13}}{f^2}\omega_{sl}$$

$$= \frac{k_{13}}{f^2} s \frac{2}{p}(2\pi f) = \frac{k_{21}}{f}$$

$$\omega_r = (1-s)\omega_s = k_{15} f$$

$$P_{em} = T_{em} \cdot \omega_r = \text{constant}$$

- The output torque capability decreases as the motor speed increases.

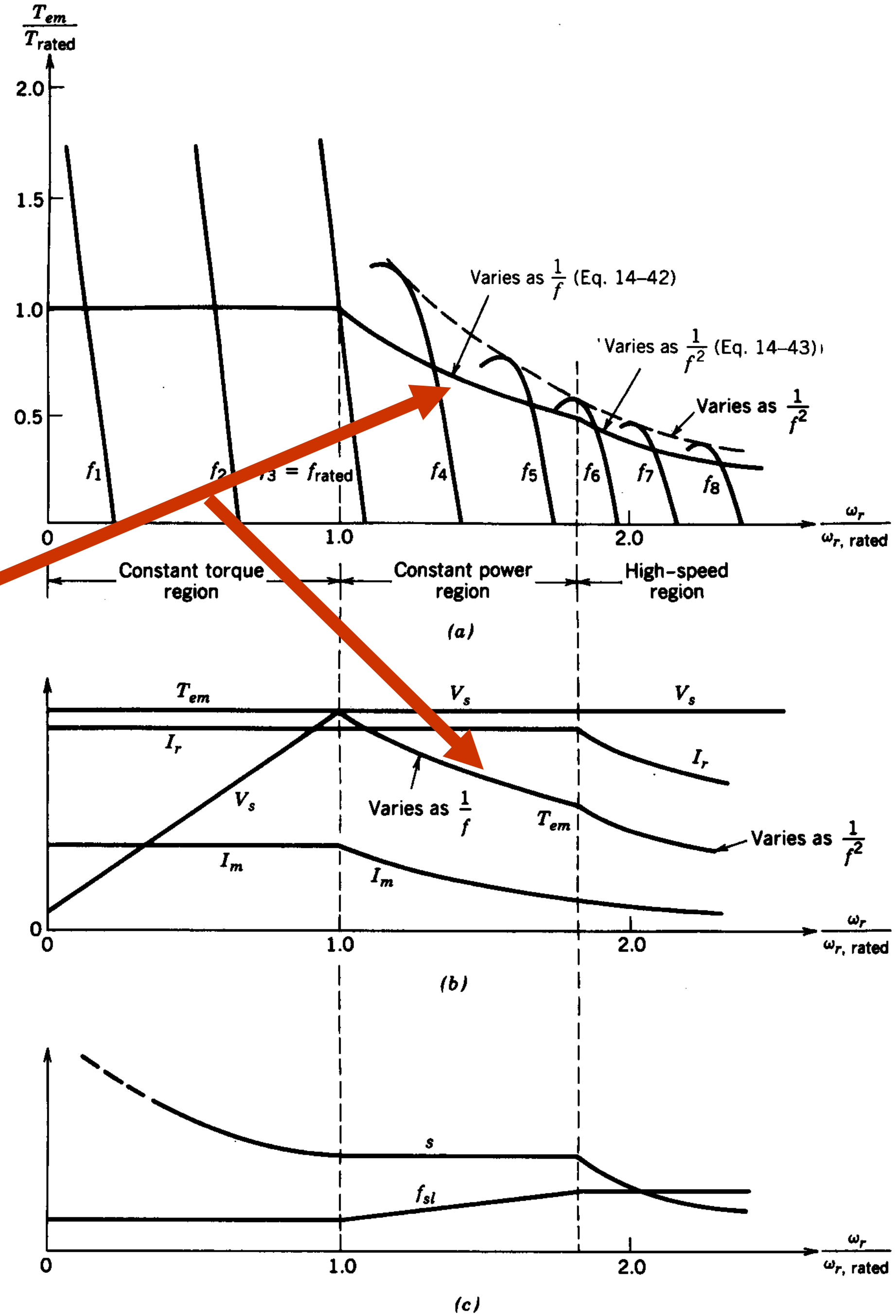


Figure 14-12 Induction motor characteristics and capabilities.

—— Speed Control by V
Frequency and Vo

High speed operation:

Constant-f_{sl} Region

- Depending on the motor design, ϕ_{ag} is reduced so much that the motor approaches its pull-out torque.

$$f_{sl} = \text{constant}$$

$$T_{em} \approx \frac{k_{13}}{f^2}\omega_{sl}$$

$$T_{em} \approx k_{16}\frac{1}{f^2}$$

- The output torque in this region is limited by the maximum torque produced by the motor.

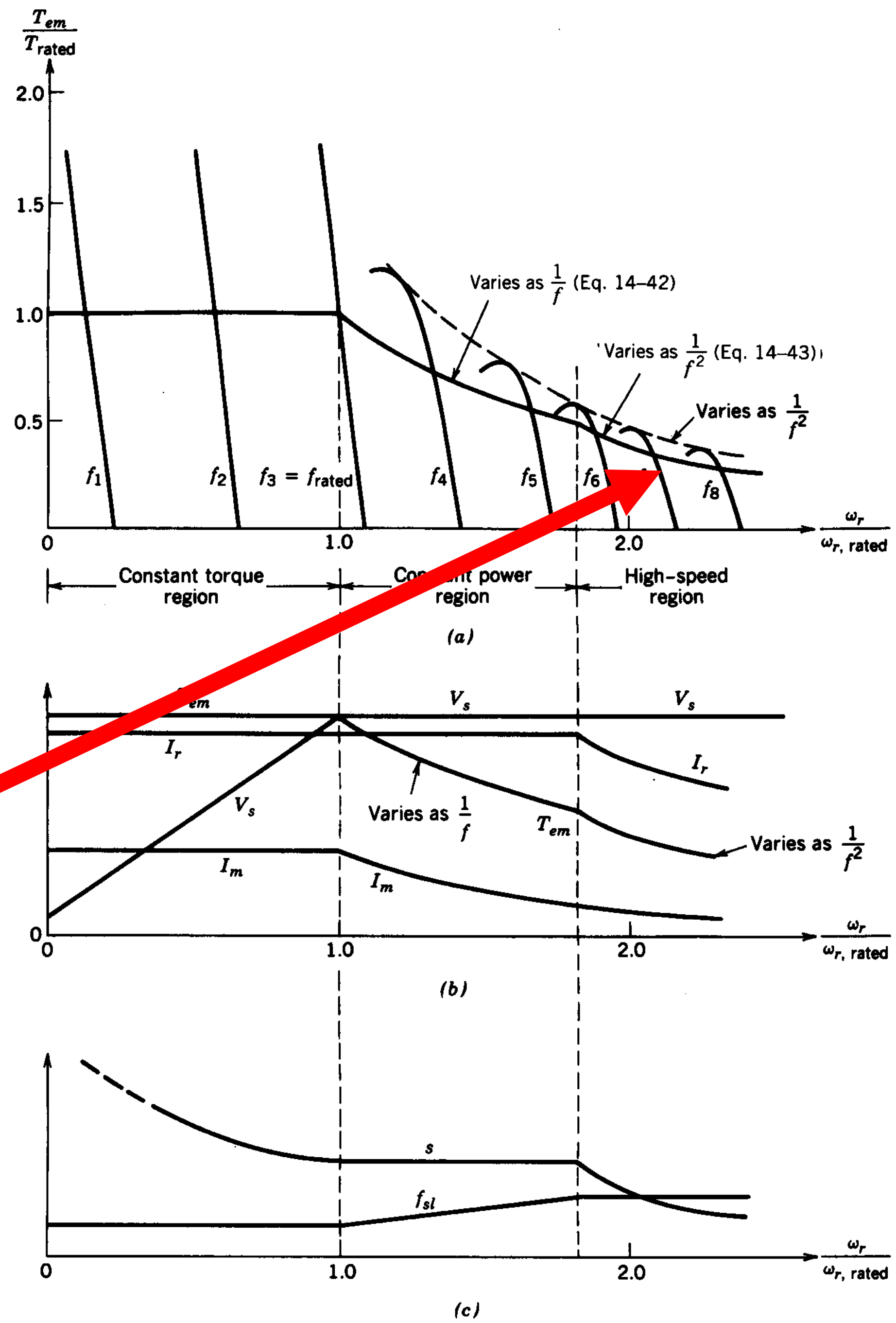


Figure 14-12 Induction motor characteristics and capabilities.

Speed Control by Varying Stator Frequency and Voltage (VVVF)

14.4.5 Braking in Induction Motors

Braking

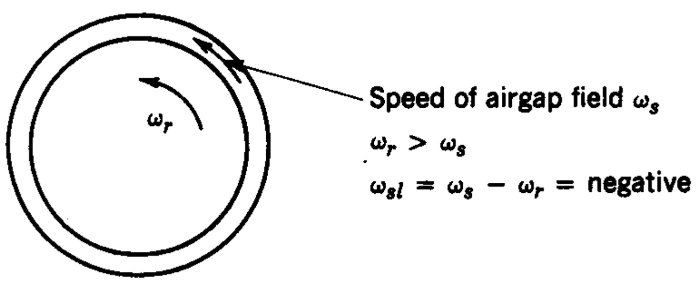
- **Mechanical braking** → The energy associated with inertia is wasted.
- **Variable-frequency control** → The energy associated with inertia is saved.

Speed Control by Varying Stator Frequency and Voltage (VVVF)

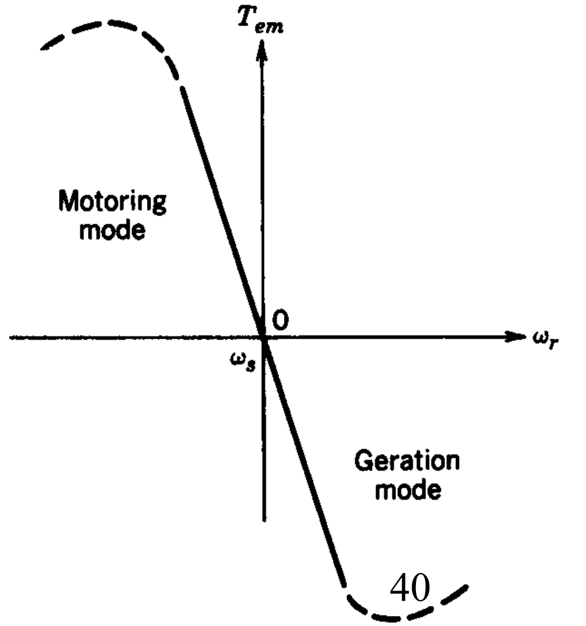
Braking
- **Mechanical braking** → The energy associated with inertia is wasted.
- **Variable-frequency control** → The energy associated with inertia is saved.

$$T_{\mathrm{em}} \approx k_9 f_{\mathrm{sl}}$$

The generation mode with a negative T_{em} is used to realize variable-frequency braking.



(a)

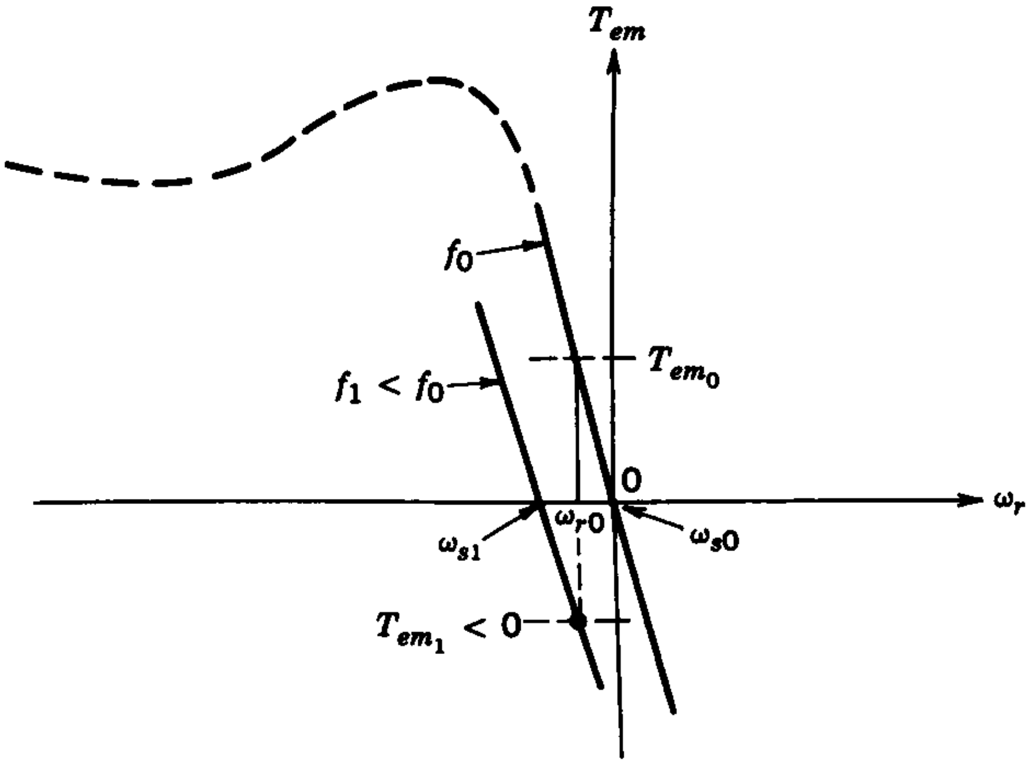


(b)

Chap.14 Induction Motor Drives

Speed Control by Varying Stator Frequency and Voltage (VVVF)

- The negative T_{em} causes the motor speed to decrease quickly and some of the energy associated with the motor-load inertia is fed into the source connected to the stator.



Braking

$$f_0 \Rightarrow f_1$$

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

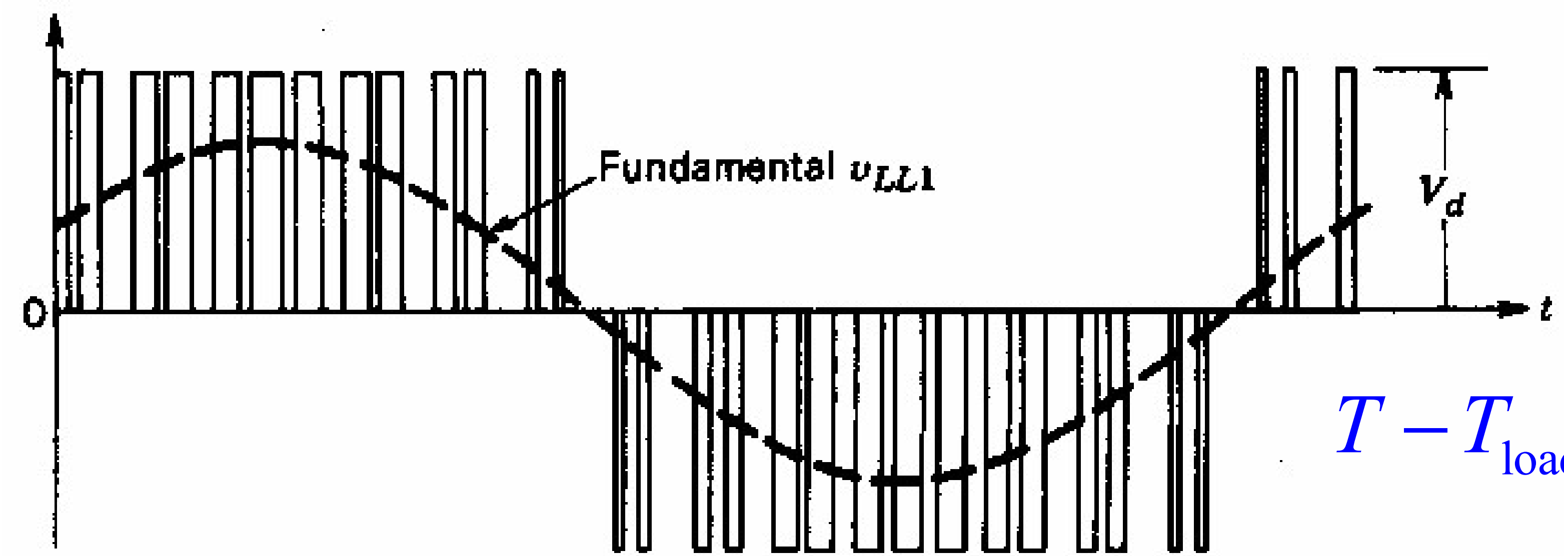
Impact of Nonsinusoidal Excitation on Induction Motors

The three phase voltages or currents produced by PWM inverters contain harmonic components with higher frequency.

Harmonics Voltages → **Harmonic Motor Currents**

Harmonics Voltages → **Harmonic Power Losses**

Harmonics Voltages → **Torque Pulsations**



$$T - T_{\text{load}} = J\frac{d\omega}{dt}$$

Impact of Nonsinusoidal Excitation on Induction Motors

14.5.1 Harmonic Motor Currents

If the stator voltage is known, the harmonic components in the motor current can be obtained by using the principle of superposition and the harmonic equivalent circuit.

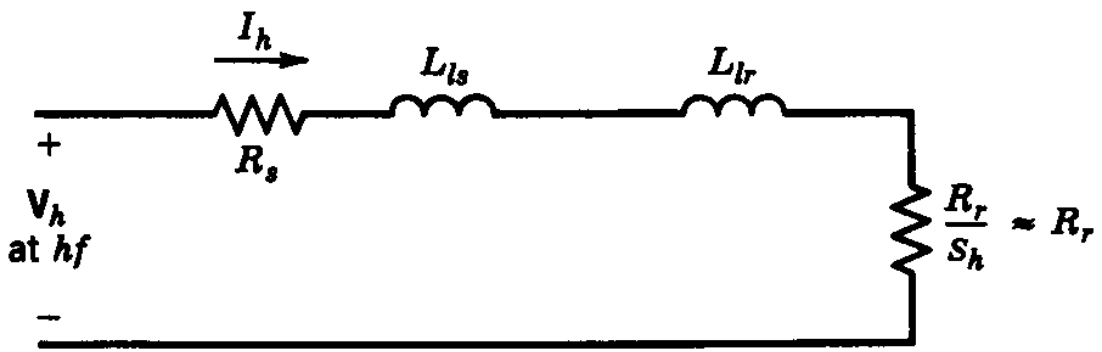


Figure 14-15 Per-phase harmonic equivalent circuit.

For calculating the harmonic currents, the magnetizing components can be neglected and the harmonic current magnitude is primarily determined by the leakage reactance at the harmonic frequency.

$$I_h \approx \frac{V_h}{h\omega(L_{ls} + L_{lr})}$$

Impact of Nonsinusoidal Excitation on Induction Motors

$$I_{\mathrm{h}} \approx \frac{V_{\mathrm{h}}}{h\omega(L_{\mathrm{ls}} + L_{\mathrm{lr}})}$$

The magnitudes of harmonic currents can be reduced by increasing the frequencies of the harmonic voltages.

14.5.2 Harmonic Power Losses

The additional power losses (copper loss, core loss and stray loss) due to harmonic currents are in a range of 10-20% of the total power losses at the rated load.

Additional copper loss

$$\Delta P_{\mathrm{cu}} = \sum_{h=2}^{\infty} (R_{\mathrm{s}} + R_{\mathrm{r}}) I_{\mathrm{h}}^2$$

Impact of Nonsinusoidal Excitation on Induction Motors

14.5.3 Torque Pulsations

Harmonics in the stator excitation

⬇

Pulsating-torque components

$$T - T_{\text{load}} = J\frac{d\omega}{dt}$$

⬇

Troublesome speed fluctuations & shaft fatigue

Variable-Frequency Controller Classifications

The basic requirements for variable-frequency converters

- Ability to adjust the frequency according to the desired output speed.
- Ability to adjust the output voltage so as to maintain a constant air gap flux in the constant-torque region.
- Ability to supply a rated current on a continuous basis at any frequency.

Chap.14 Induction Motor Drives

Variable-Frequency Controller

Clas

Pulse-width-modulated voltage source inverter with a diode rectifier

Diode rectifier (Chap.5)

Square-wave (six-step) voltage source inverter with a thyristor rectifier

Line-voltage-commutated controlled converter (Chap.6)

Current source inverter with a thyristor rectifier

(Chap.8)

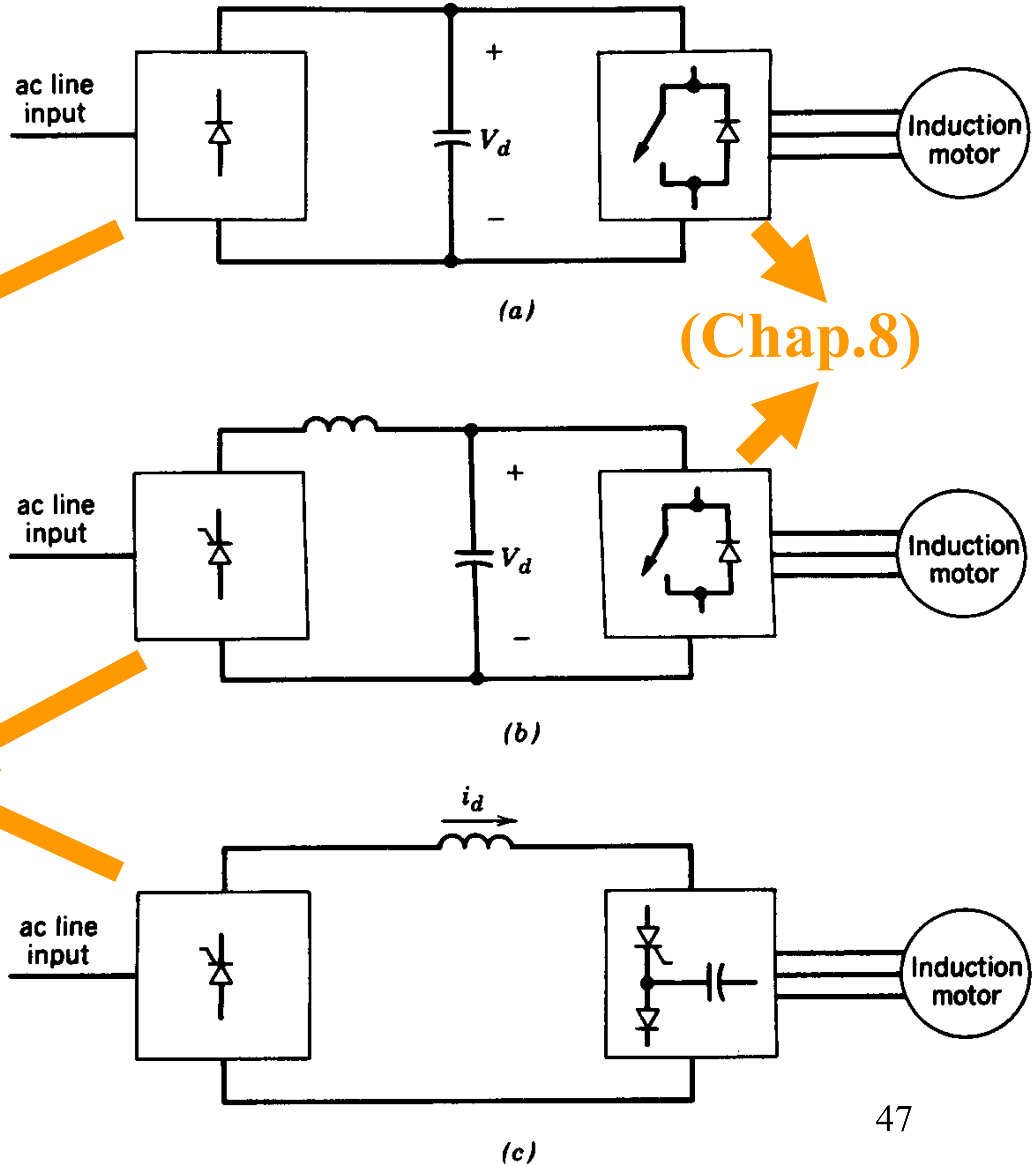
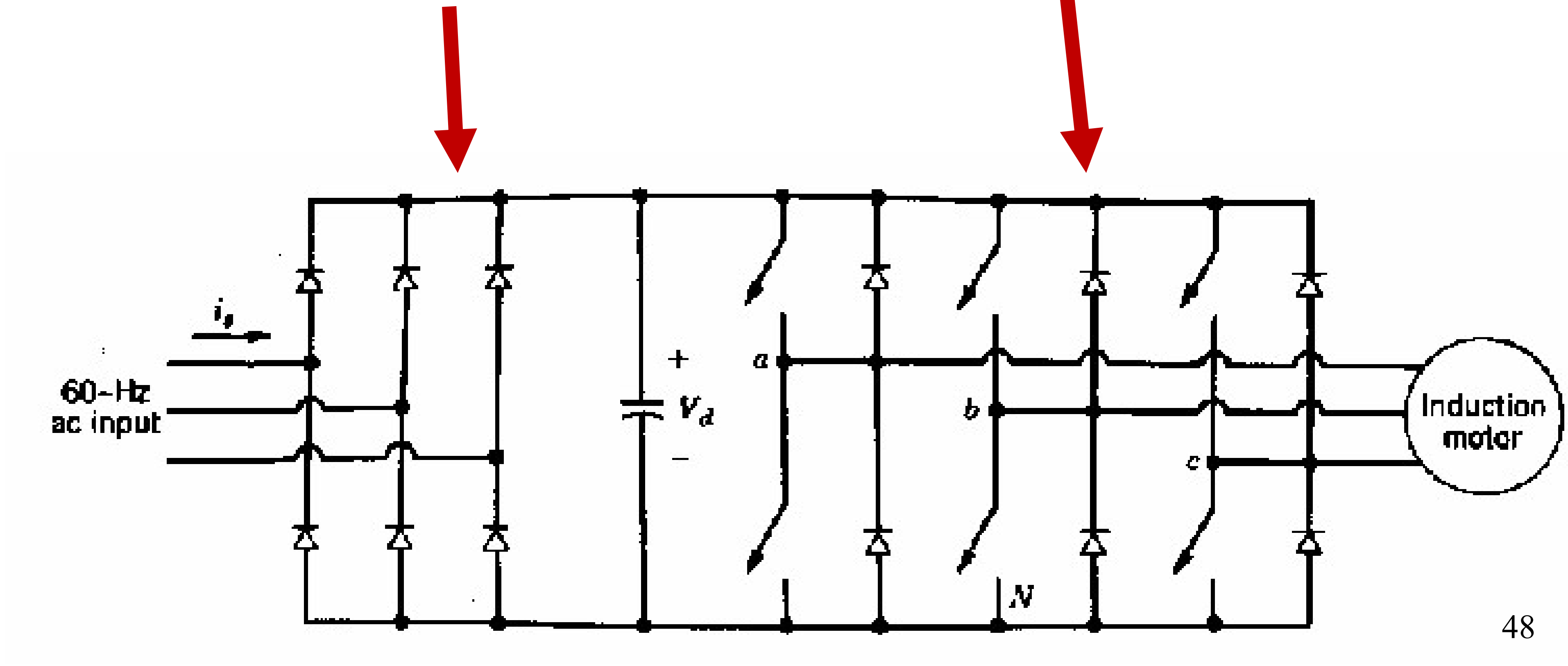


Figure 14-18 Classification of variable-frequency converters:

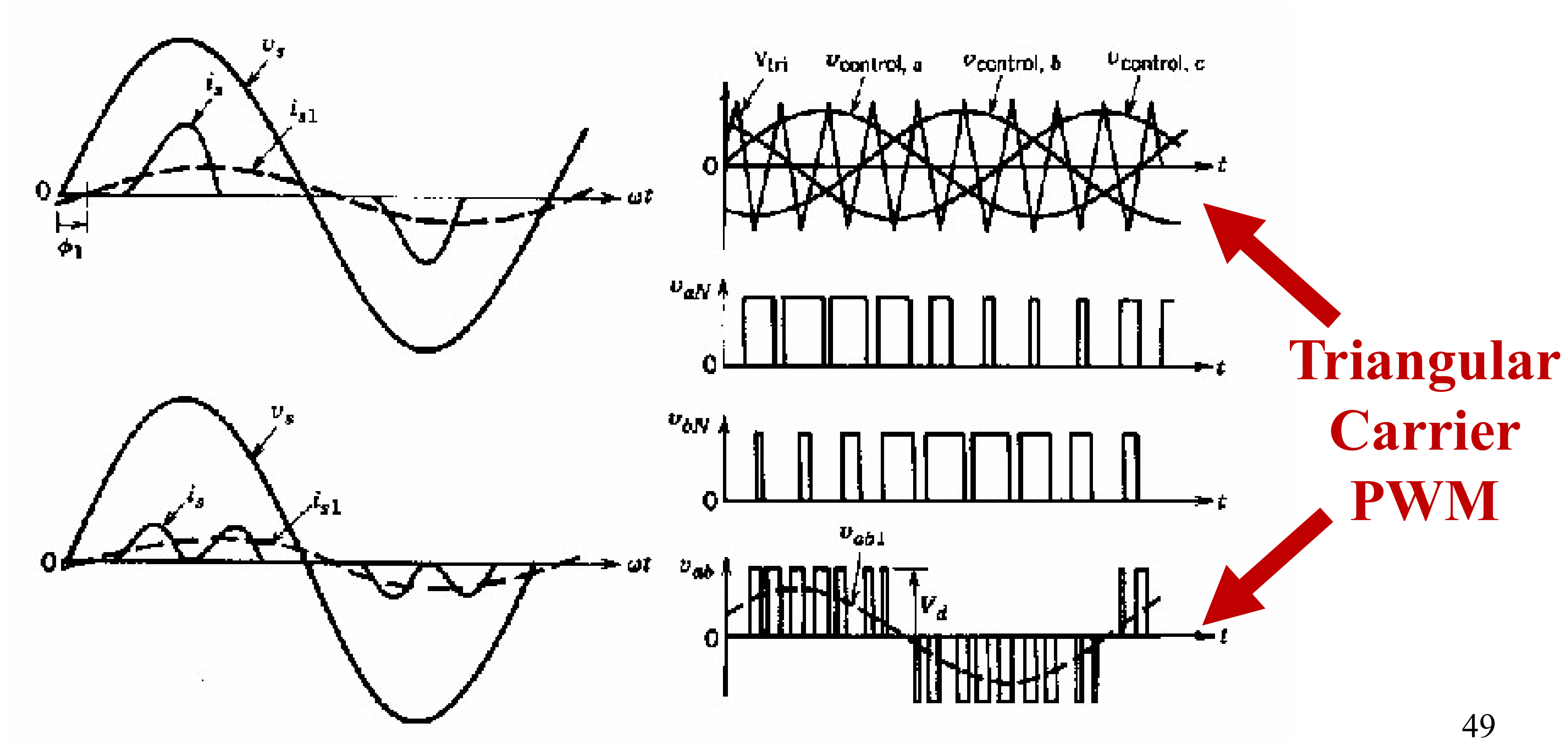
Variable-Frequency PWM-VSI Drives

• A PWM inverter controls both the frequency and the magnitude of the voltage output.
• An uncontrolled diode bridge rectifier is generally used at the input.



Variable-Frequency PWM-VSI Drives

• In a PWM inverter, the harmonics in the output voltage appear as sidebands of the switching frequency and its multiples.



Variable-Frequency PWM-VSI Drives

14.7.1 Impact of PWM-VSI Harmonics

Harmonic voltages are at high frequency. $\xrightarrow{\text{High leakage reactance}}$ Motor current ripple is small.

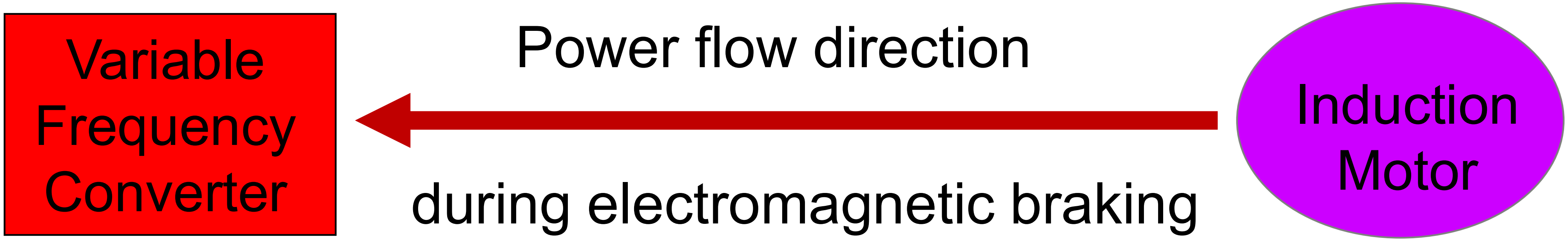
Harmonic voltages have high amplitudes. $\rightarrow$ Iron losses (eddy current & hysterisis) dominate.

14.7.2 Input Power Factor & Current Waveforms

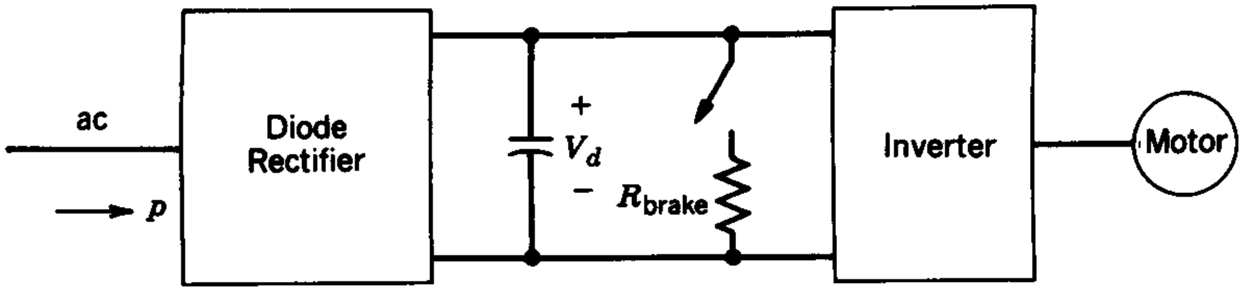
- The input ac current drawn by the rectifier of a PWM-VSI drive contains a large amount of harmonics.
- The power factor at the utility system is essentially independent of the motor power factor and the drive speed.

Variable-Frequency PWM-VSI Drives

14.7.3 Electromagnetic Braking

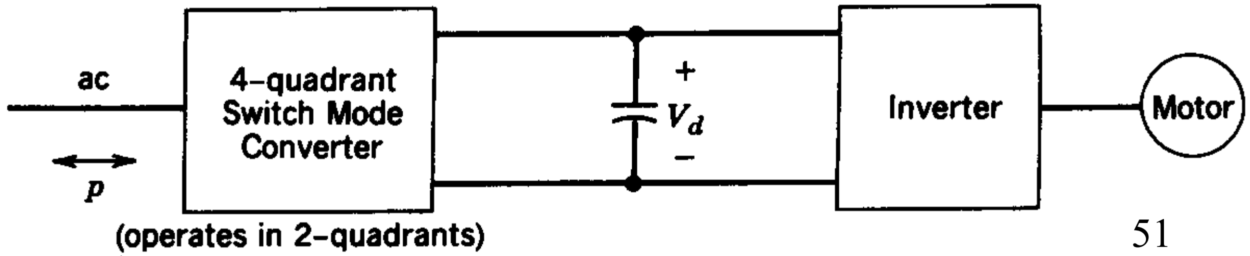


Energy Dissipation



(a)

Energy Efficient



(b)

Variable-Frequency PWM-VSI Drives

14.7.4 Adjustable-Speed Control

• In VSI drives, the speed can be controlled without a speed feedback loop, where there may be a slower acting feedback loop (dc current feedback) through the process controller.

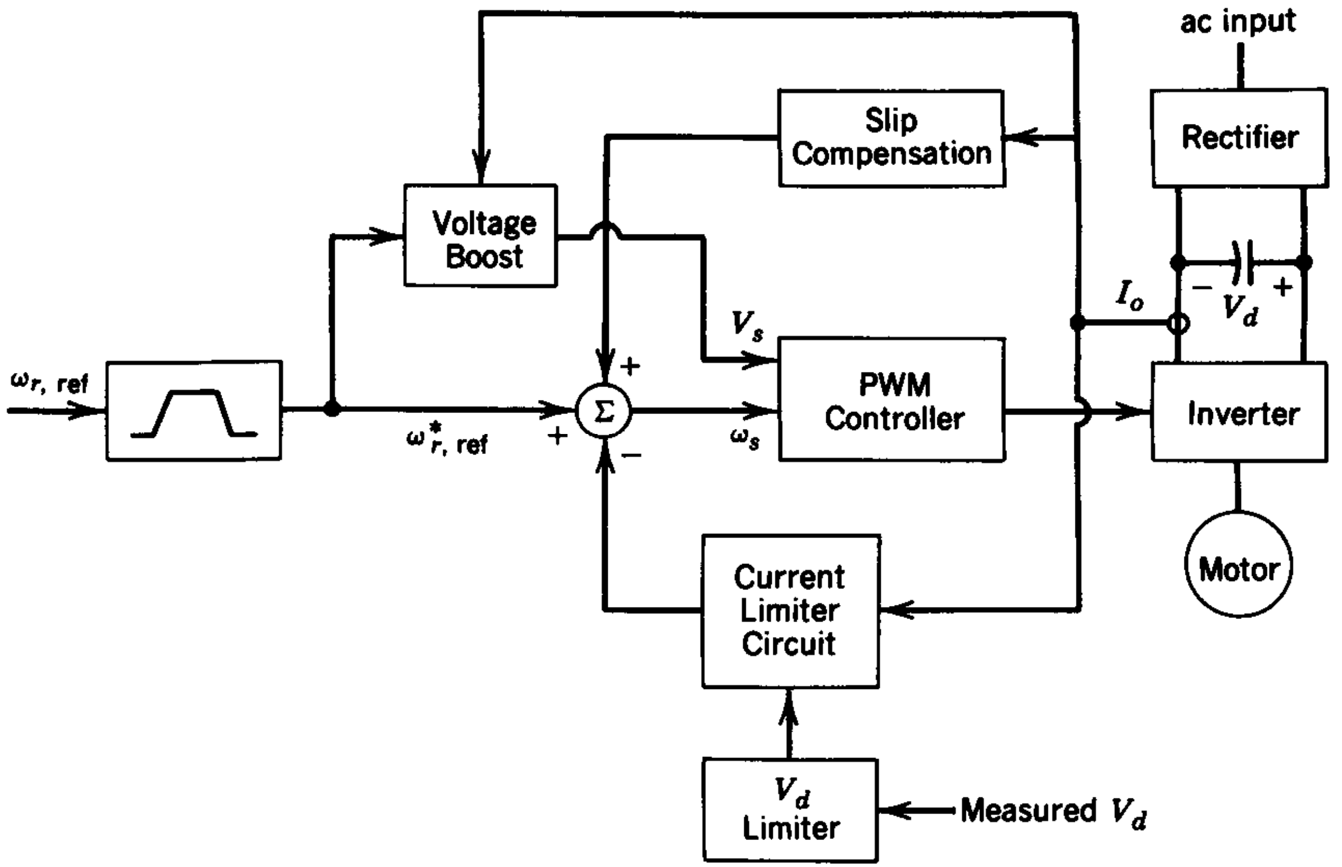


Figure 14.21 Speed control circuit. Motor speed is not measured.

Variable-Frequency PWM-VSI Drives

14.7.4 Adjustable-Speed Control

$$\omega_s = \omega_{r,ref} + k_{18} T_{em} \quad P = T_{em}\omega_{r,ref} = V_d I_o$$

To keep ϕ_{ag} constant

$$V_s = k_{19}\omega_s + k_{20} T_{em}$$

Ramp limiter

To limit the motor current stays below the current limit when there is not ramp limiter.

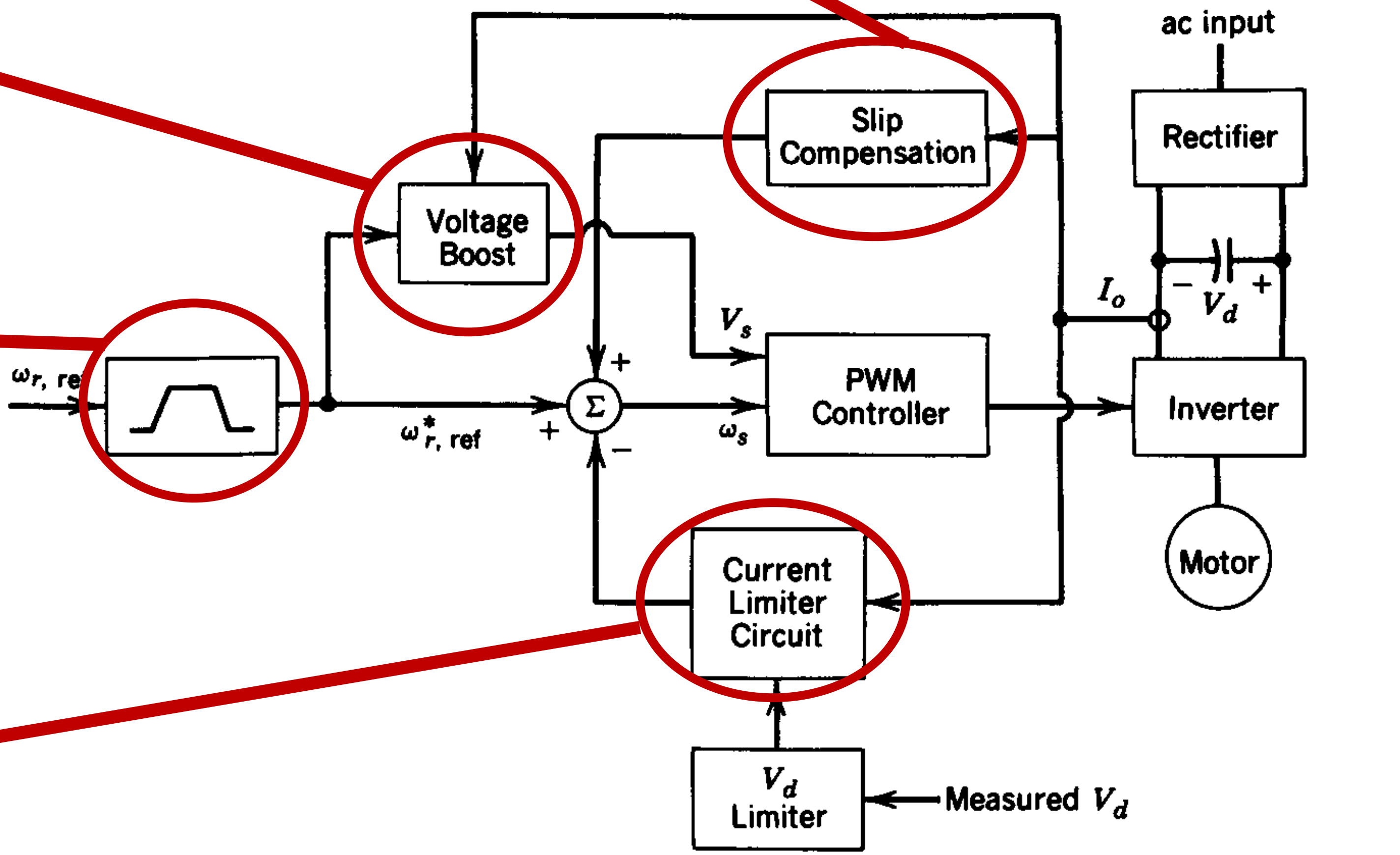


Figure 14-21 Speed control circuit. Motor speed is not measured.

Chap.14 Induction Motor Drives

Variable-Frequency PWM-VSI Drives

14.7.5 Induction Motor Servo Drives

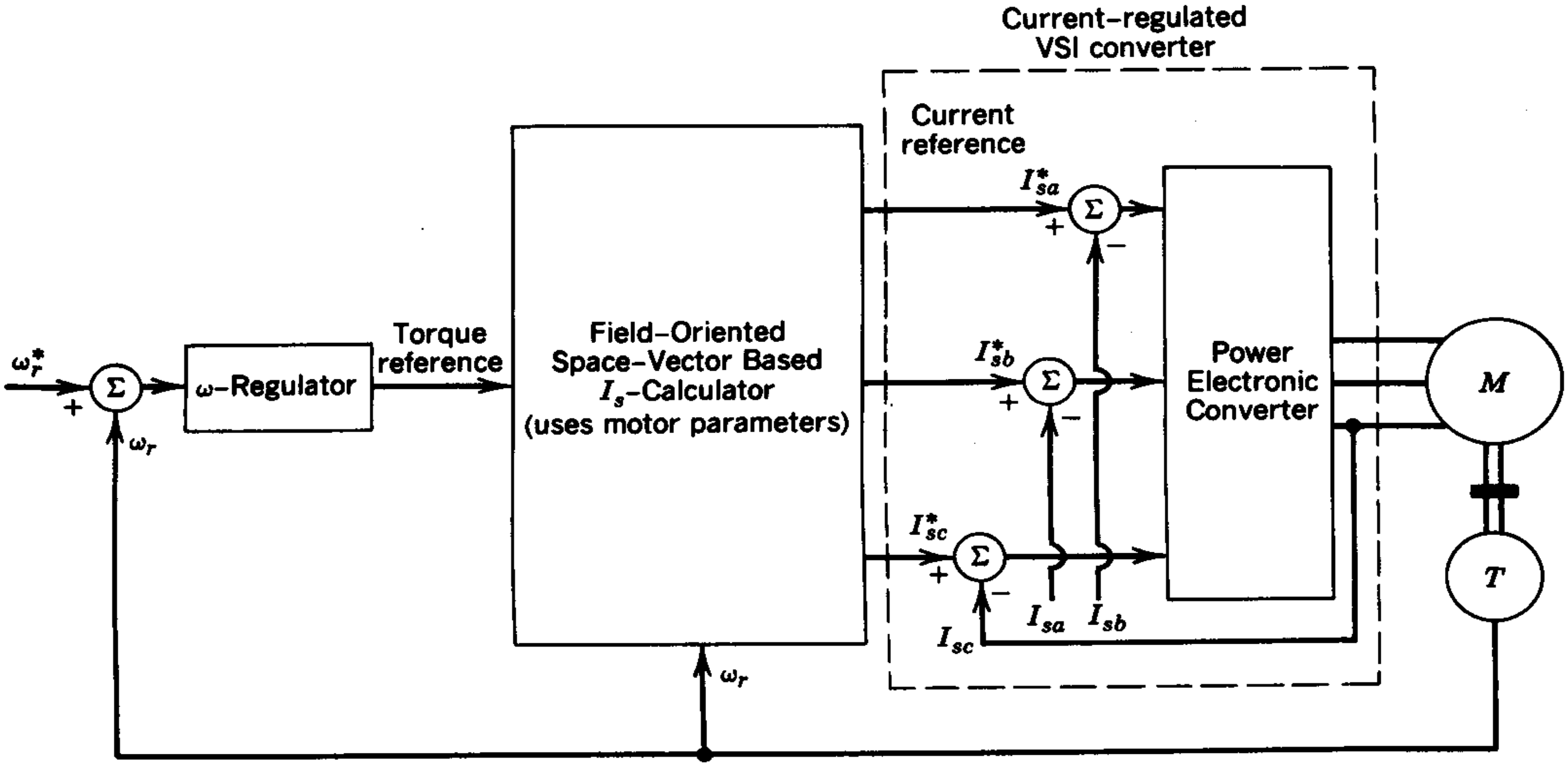
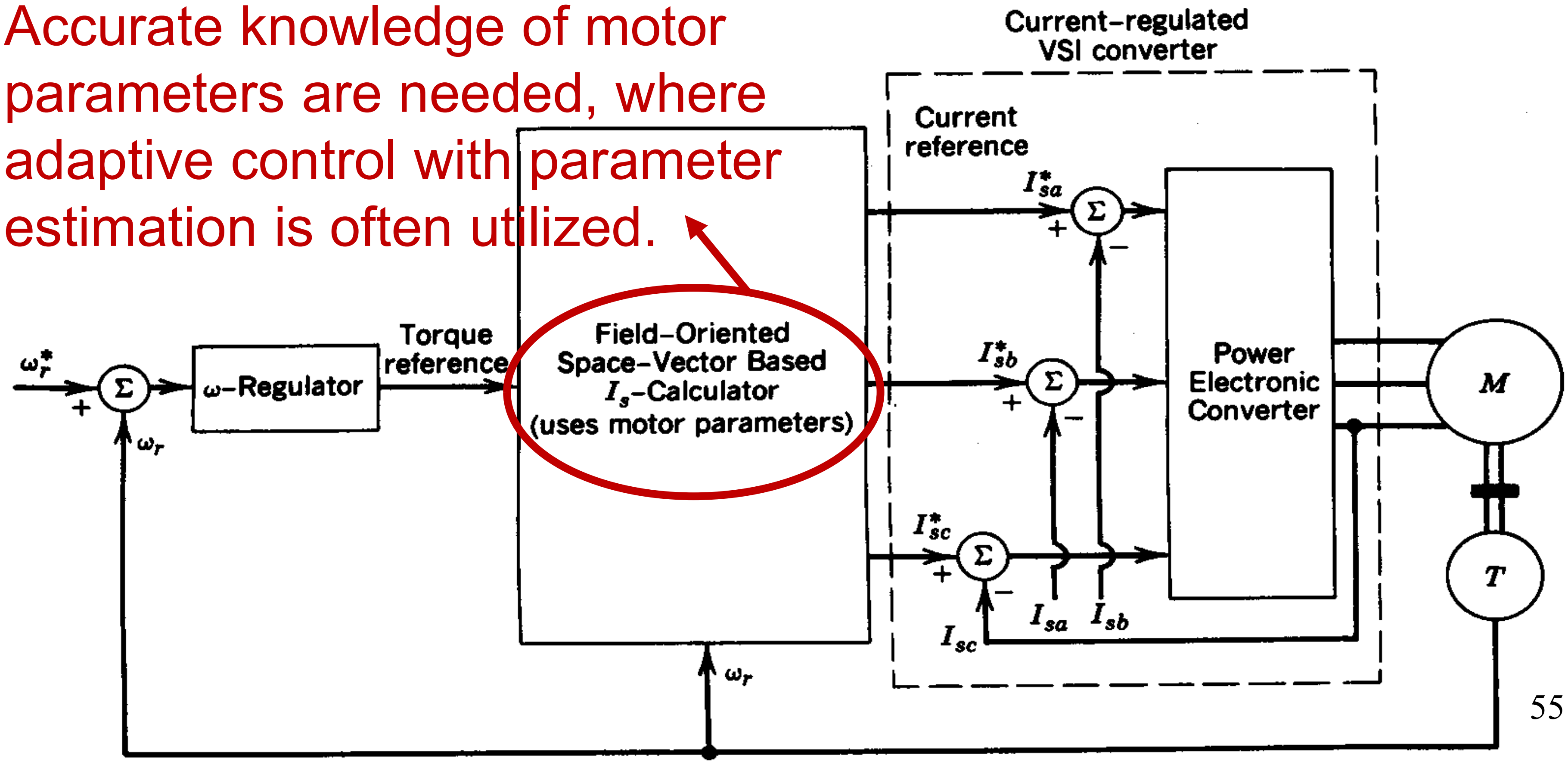


Figure 14-23 Field-oriented control for induction motor servo drive.

Variable-Frequency PWM-VSI Drives

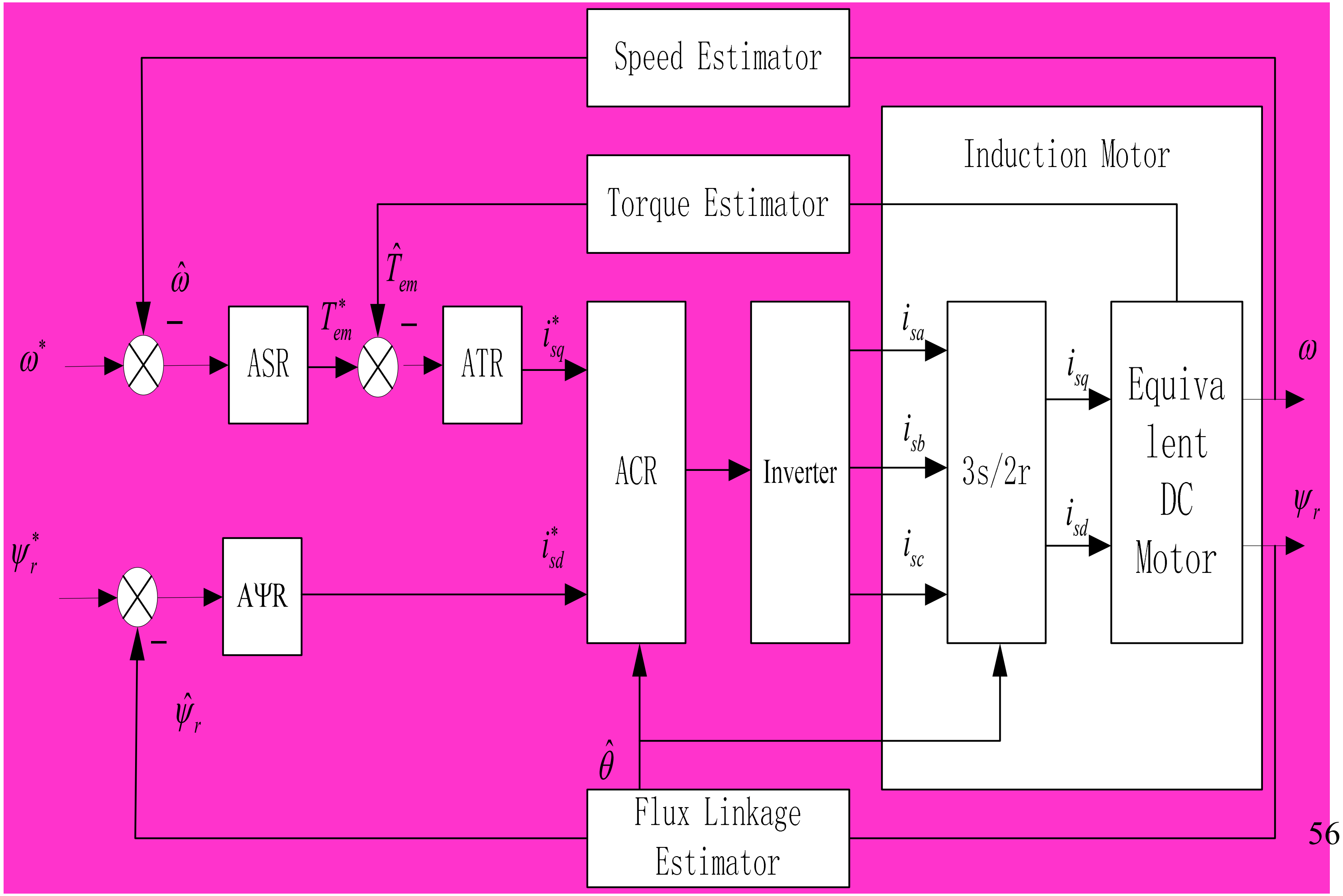
- In servo drives, the torque developed by the motor should respond quickly and precisely to the torque command without oscillation, since these drives can be used for position control.

Accurate knowledge of motor parameters are needed, where adaptive control with parameter estimation is often utilized.



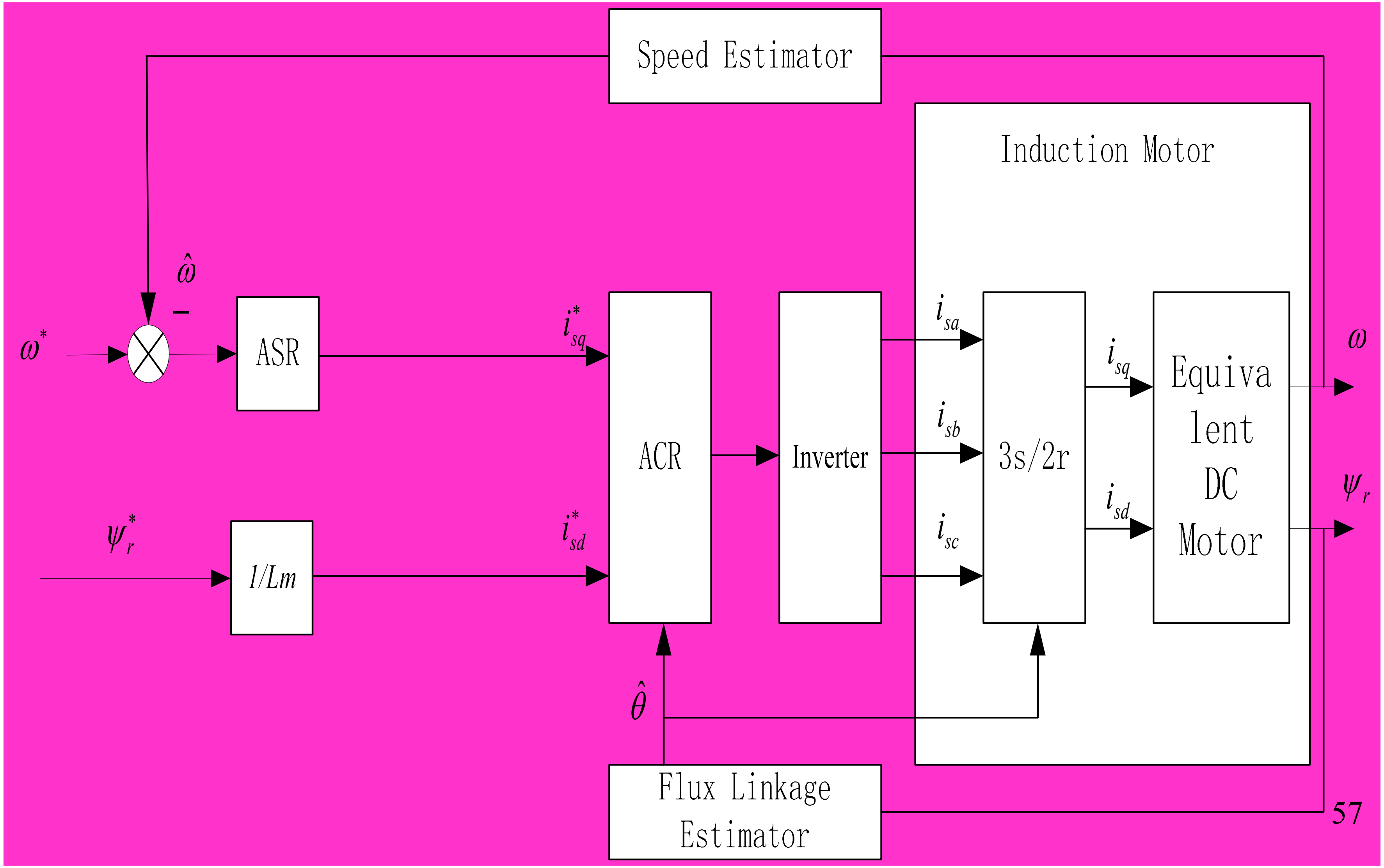
—— Variable-Frequency PWM-VSI Drives ——

Control diagram of rotor flux oriented vector control of induction motors



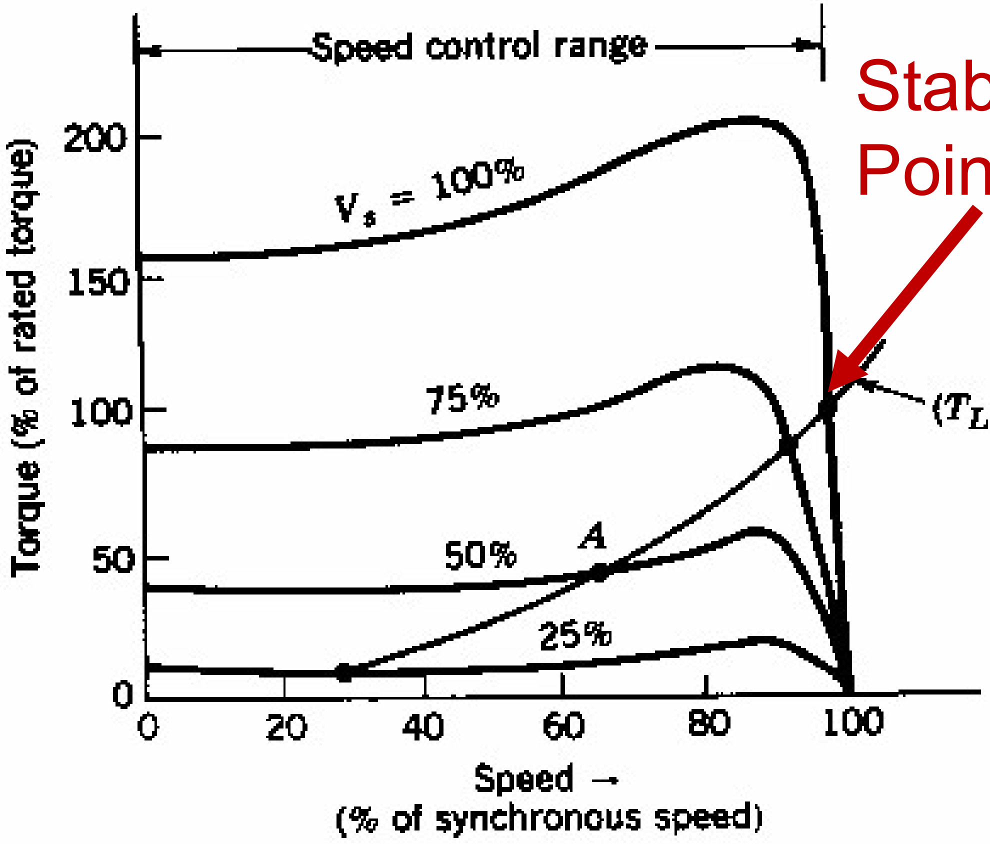
Variable-Frequency PWM-VSI Drives

Simplified rotor flux oriented vector control of induction motors



Line-Frequency Variable-Voltage Drives

- In some applications, line-frequency variable-voltage drive is a cheaper solution than VVVF drive.
- The torque T_{em} is proportional to V_s^2 for a value of rotor speed determined by f (equal to the line frequency) and fixed f_{sl}.



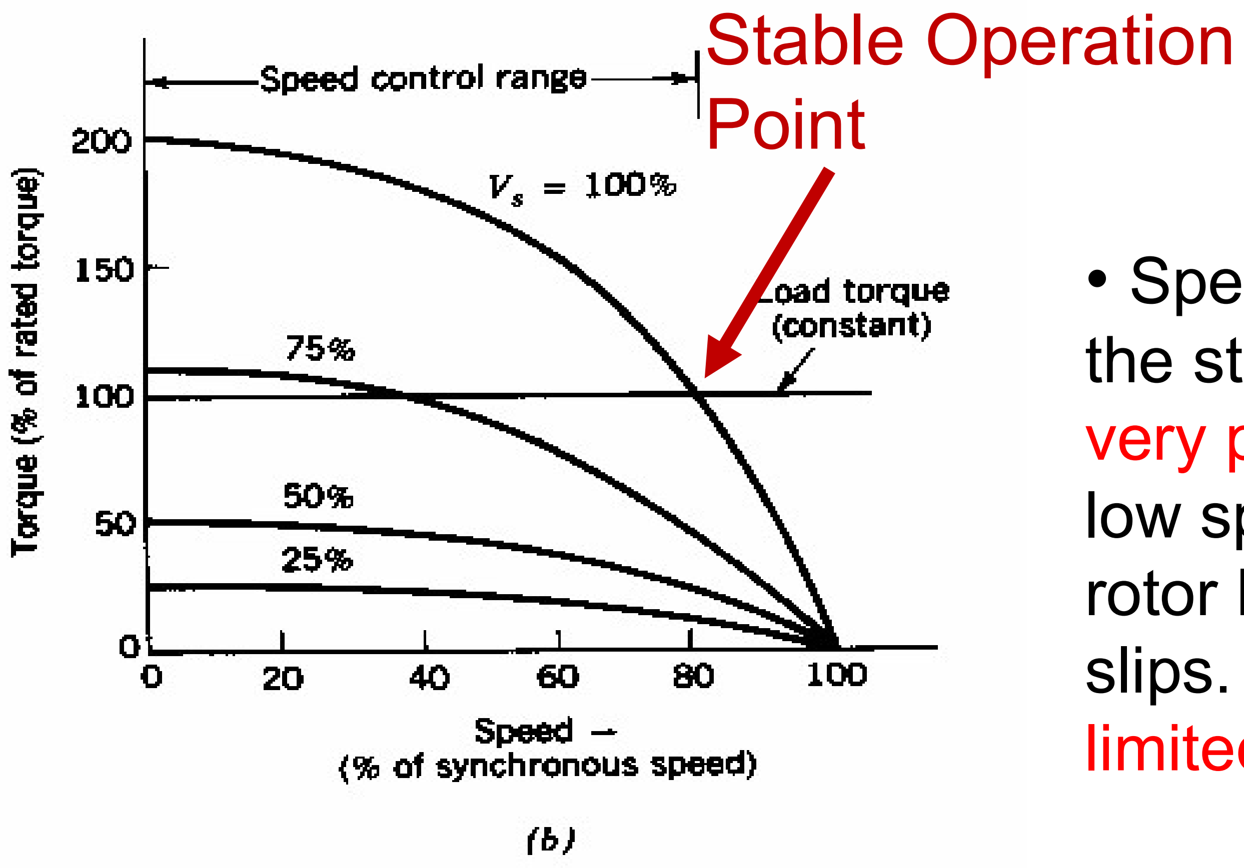
Stable Operation Point

$$T_{em} = k_{21} V_s^2$$

The operation point would not be stable if the load torque remained constant with speed.

Line-Frequency Variable-Voltage Drives

- For a load requiring a constant torque with speed, a motor with a higher resistance, which has a large value of slip at which the pull-out torque is developed, should be used.



$$\%P_r = \frac{P_r}{P_{em}} = \frac{f_{sl}}{f - f_{sl}}$$

- Speed control by controlling the stator voltage results in a very poor energy efficiency at low speeds because of high rotor losses caused by large slips. Hence, this technique is limited to low power applications.

Summary

1. Induction motors are the workhorse of industry because of their low cost and rugged construction.
2. In a three-phase induction motor, the resultant field distribution in the air gap is sinusoidal and rotates at a synchronous speed.
3. The speed of an induction motor can be controlled by varying the stator frequency, which controls the synchronous speed and, hence, the motor speed, since the slip is kept small.
4. For braking in an induction motor to reduce its speed, the stator frequency is decreased so that the synchronous speed at which the air gap magnetic field rotates is less than the rotor speed.

Summary

5. Switch-mode dc-to-ac inverters, as discussed in Chapter 8, are used to supply adjustable-frequency, adjustable-magnitude three-phase ac voltages for induction motor speed control.
6. The inverters used for the induction motor speed control can be classified as pulse-width-modulated voltage source inverters, square-wave voltage source inverters and current source inverters.
7. By means of field-oriented vector control, induction motor drives can be used for servo applications.

Chap.14 Induction Motor Drives

Vocabulary

1. permanent magnet	n.	永磁
2. servo drive	n.	伺服传动
3. armature winding	n.	电枢绕组
4. excited field winding	n.	励磁绕组
5. line frequency	n.	工频
6. field flux weakening	n.	弱磁
7. variable-frequency controller	n.	变频控制器
8. wound-rotor	n.	绕线式转子
9. regeneration	n.	回馈, 再生
10. soft start	n.	软起动
11. input power factor	n.	输入功率因数
12. sideband	n.	频带
13. blower	n.	鼓风机
14. centrifugal pump	n.	离心泵
15. throttling valve	n.	节流阀
16. shaft fatigue	n.	轴老化