7 Frequency-controlled induction motor drives

- The relationship between the synchronous speed and the frequency

$$n_s = \frac{120 f_s}{P}$$

- 7.2 Static frequency changes
- There are two types

direct: cycloconverters

indirect: a rectification and an inverter

• Cycloconverter drive

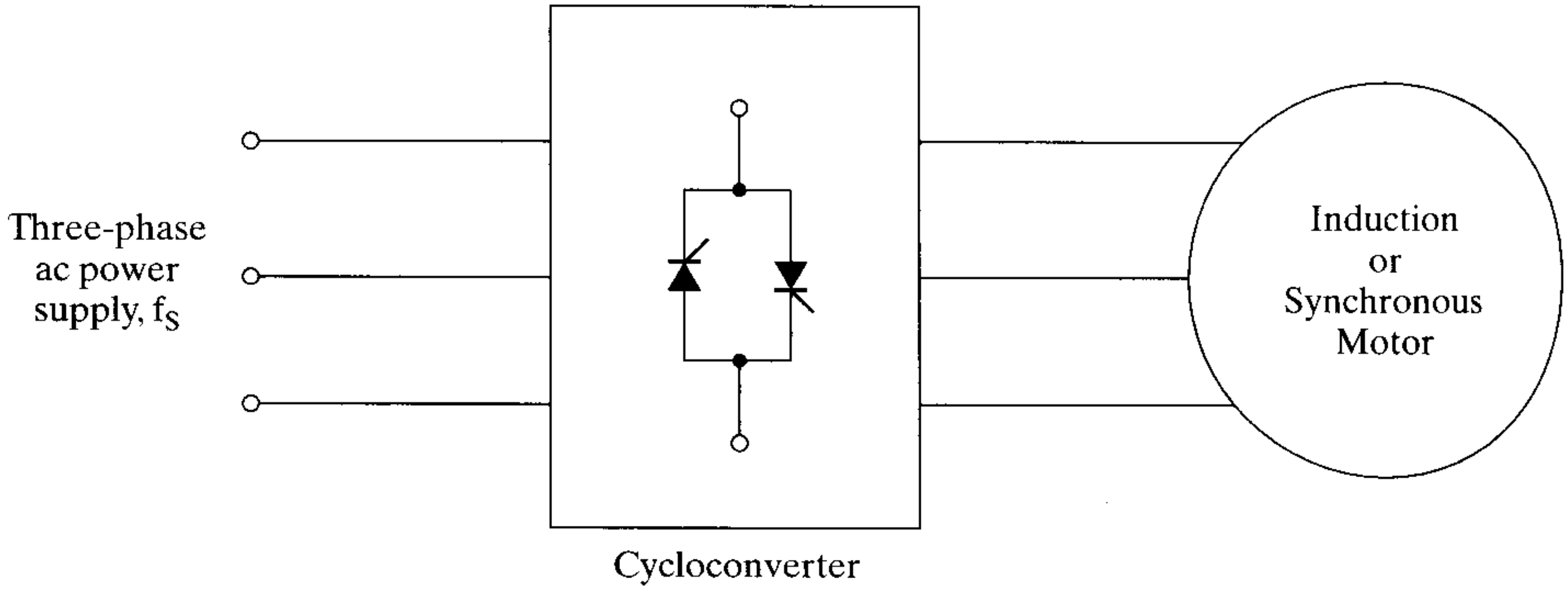

Figure 7.1 Cycloconverter-driven induction or synchronous motor drive

• PWM inverter

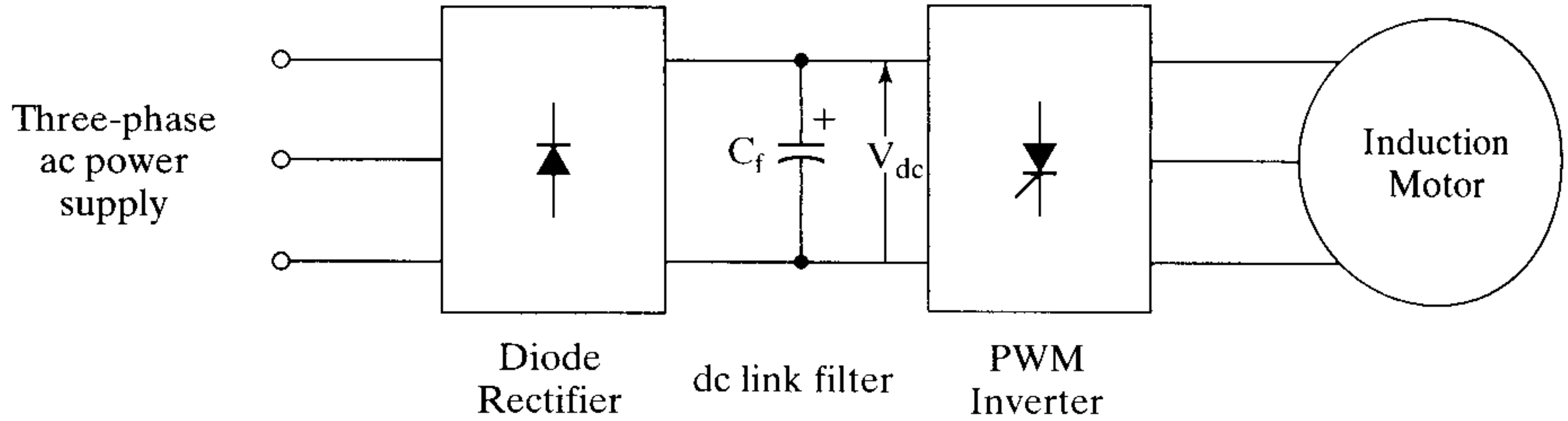

Figure 7.2 PWM inverter fed induction motor drive

- Direct (cycloconverter): The output frequency has a range of from 0 to o.5f_s. 0.33f_s for better waveform control.
- Indirect: broadly classified depending on the feeding source, voltage or current source
- Variable-voltage, variable-frequency drive

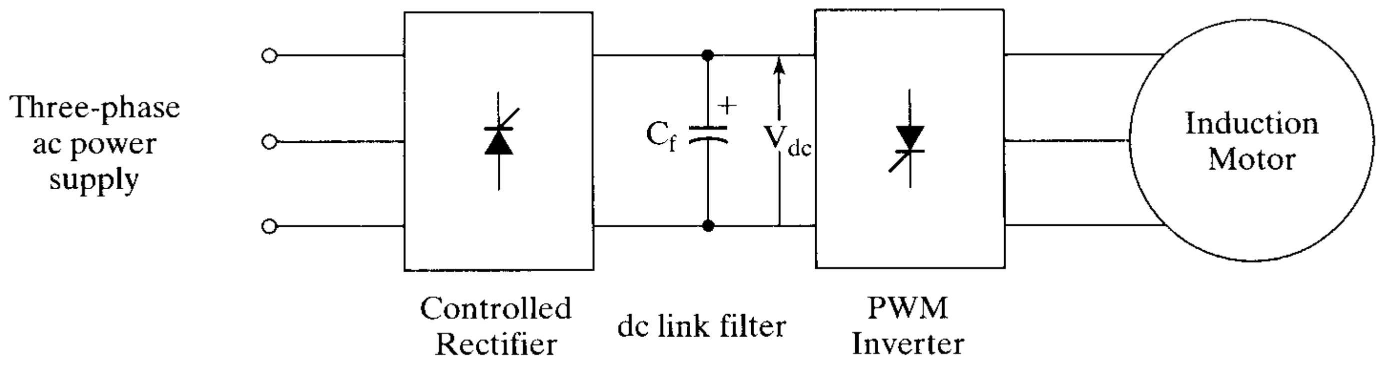

Figure 7.3 Variable-voltage, variable-frequency (VVVF) induction motor drive

- Regenerative voltage-source inverter-fed ac drive

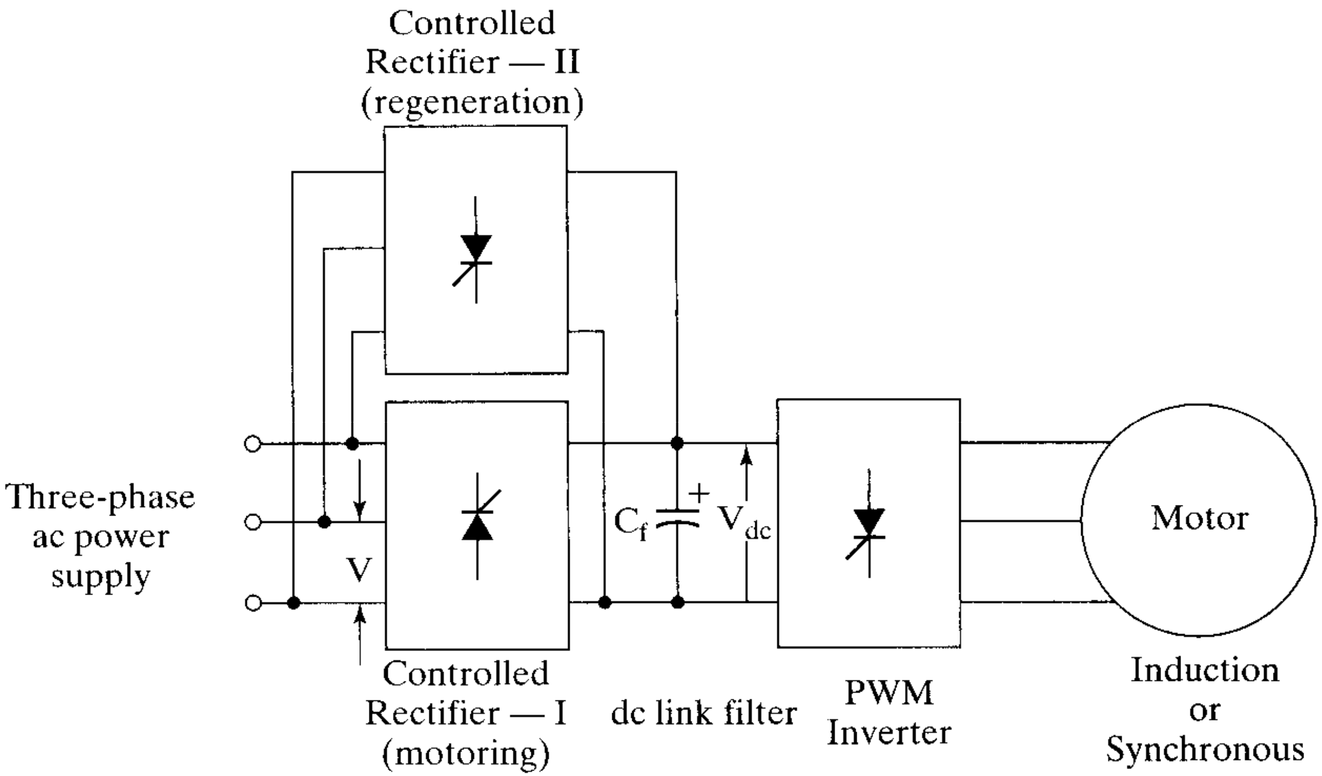

Figure 7.4 Regenerative voltage-source inverter-fed ac drive

- Current-regulated voltage-source-driven drive

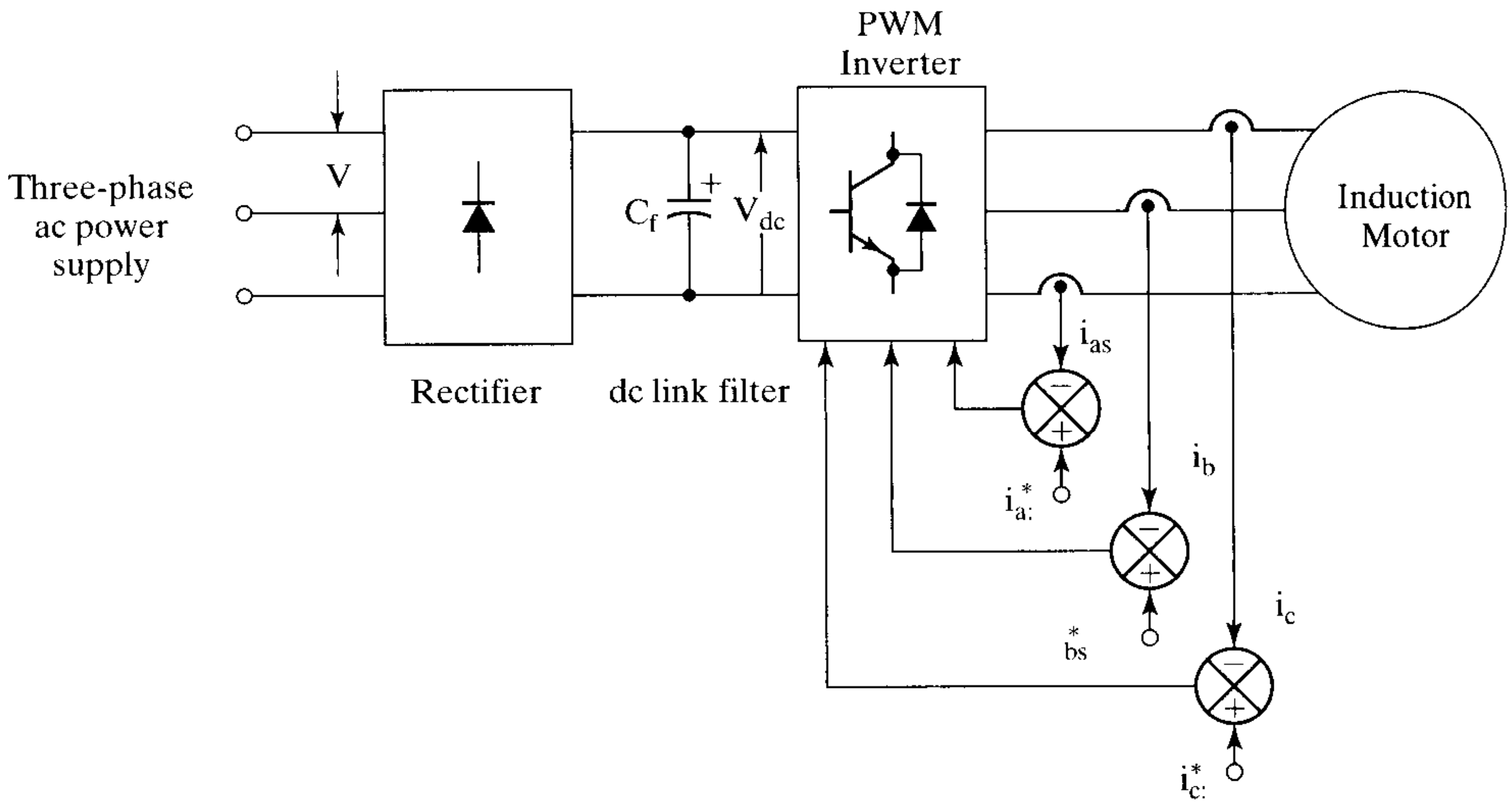

Figure 7.5 Current-regulated voltage-source-driven induction motor drive

• Current-source inverter-driven drive

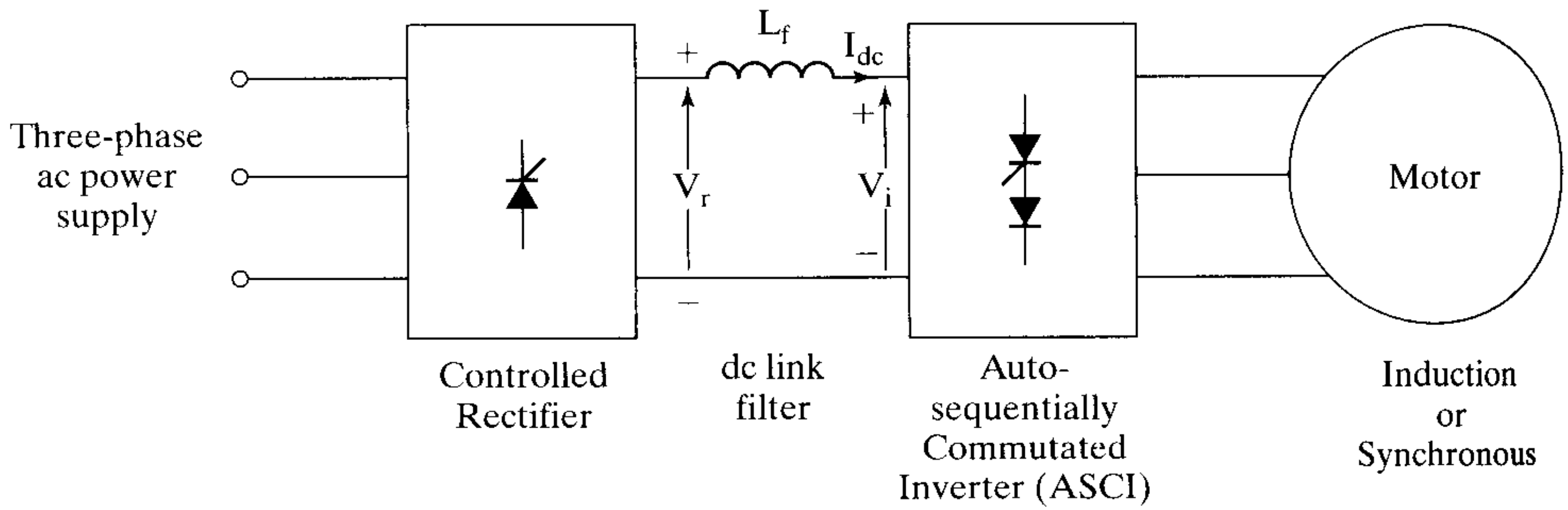

Figure 7.6 Current-source inverter-driven induction or synchronous motor drive

• Classification of frequency changer

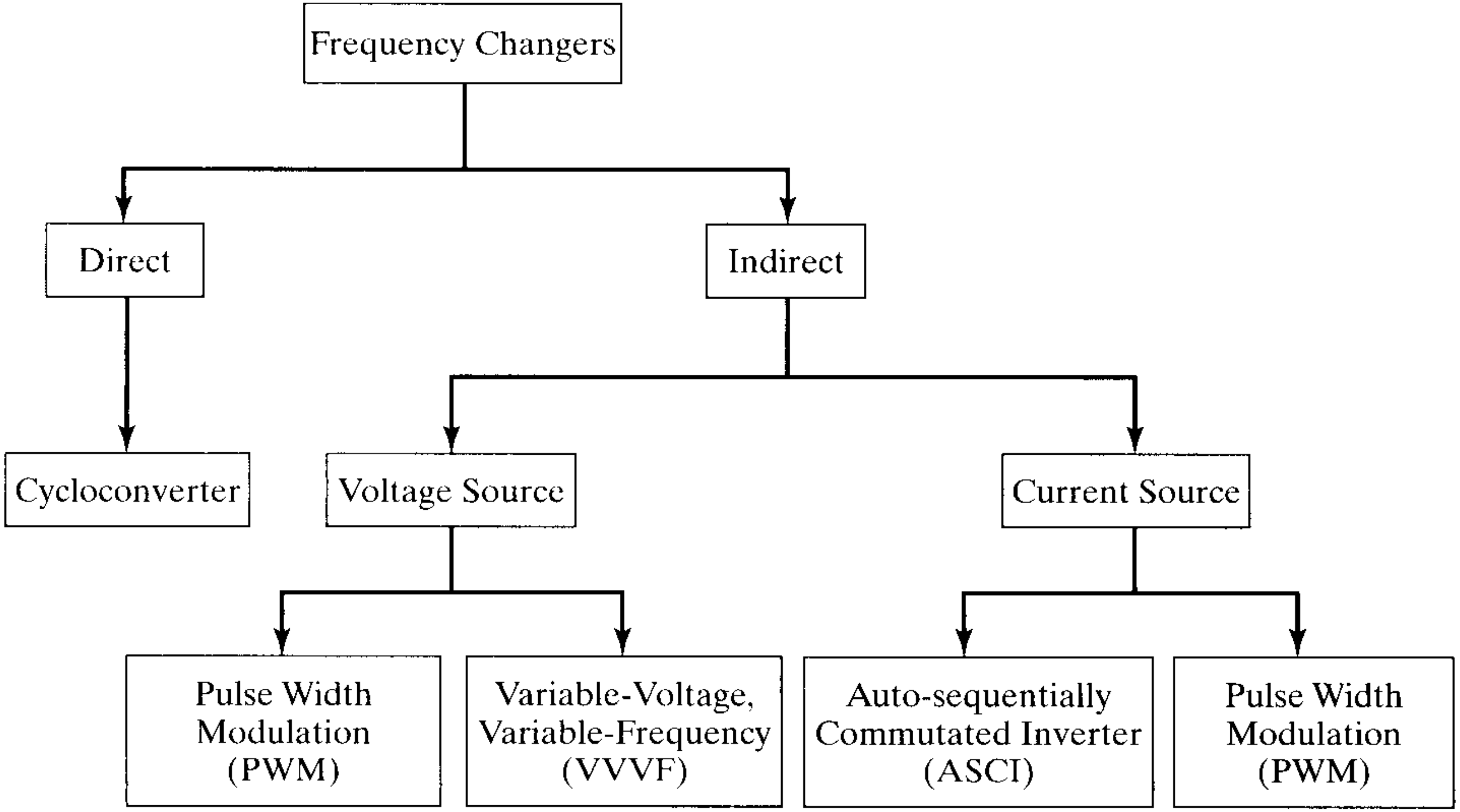

Figure 7.7 Classification of frequency changers

7.3 Voltage-source inverter

- A half-bridge modified McMurray inverter.

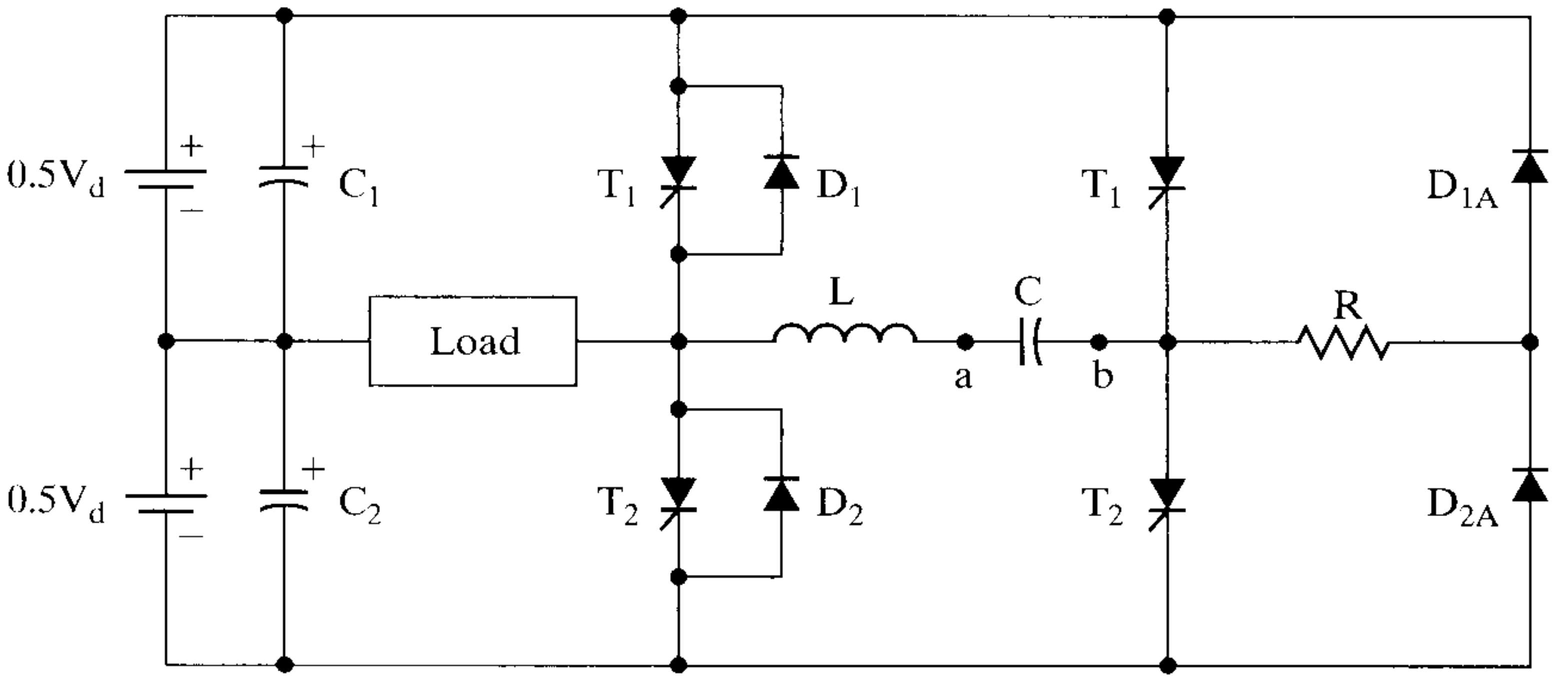

Figure 7.8 Half-bridge voltage-source inverter

- Snubbers: across transistors or SCR to limit dv/dt and its effects.
- (a) Half-bridge inverter charging

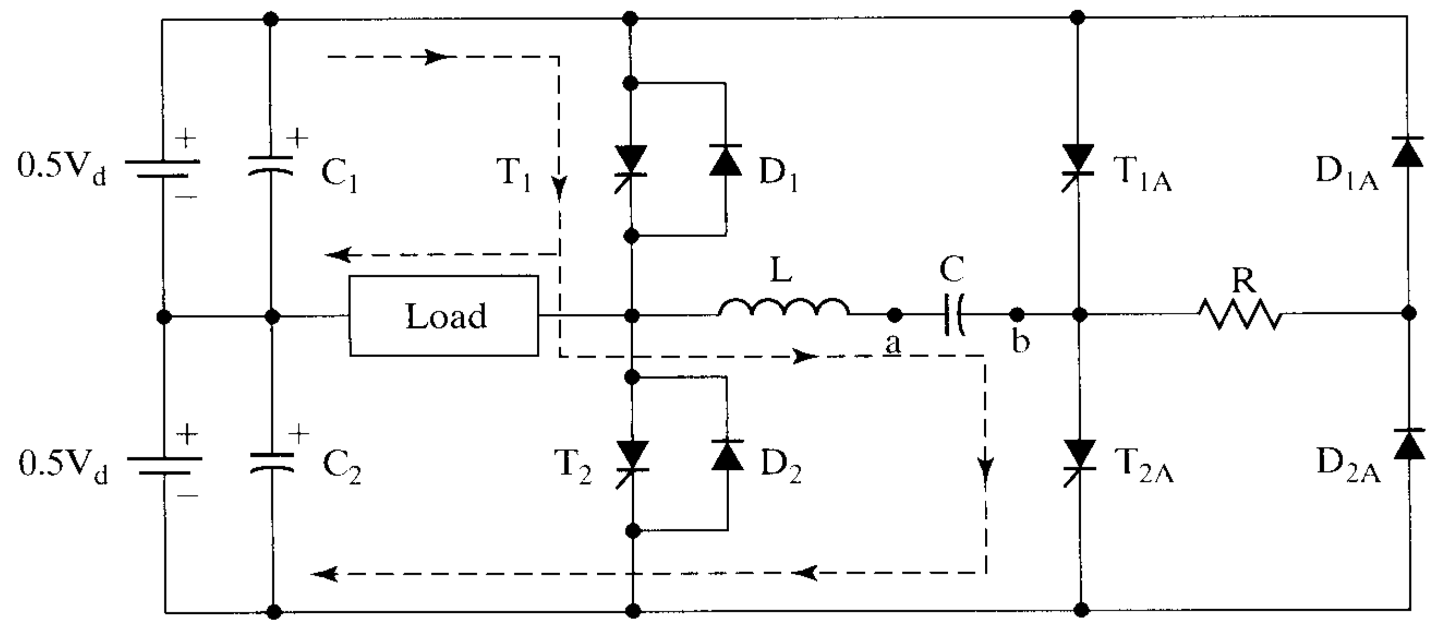

Figure 7.9a (a) Half-bridge voltage-source inverter charging

- (b) Half-bridge inverter communication

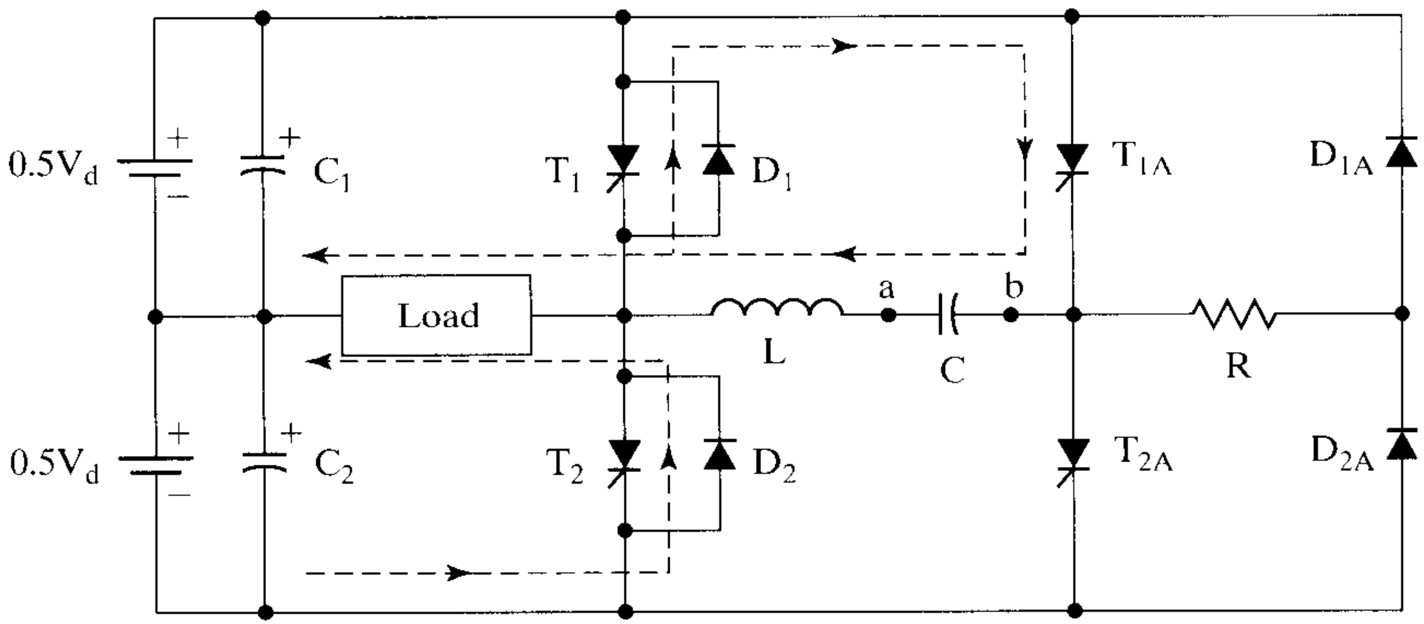

Figure 7.9b (b) Half-bridge voltage-source inverter commutation

- The frequency of the load voltage is determined by the rate at which T_1 and T_2 are enabled.
- A full-bridge inverter

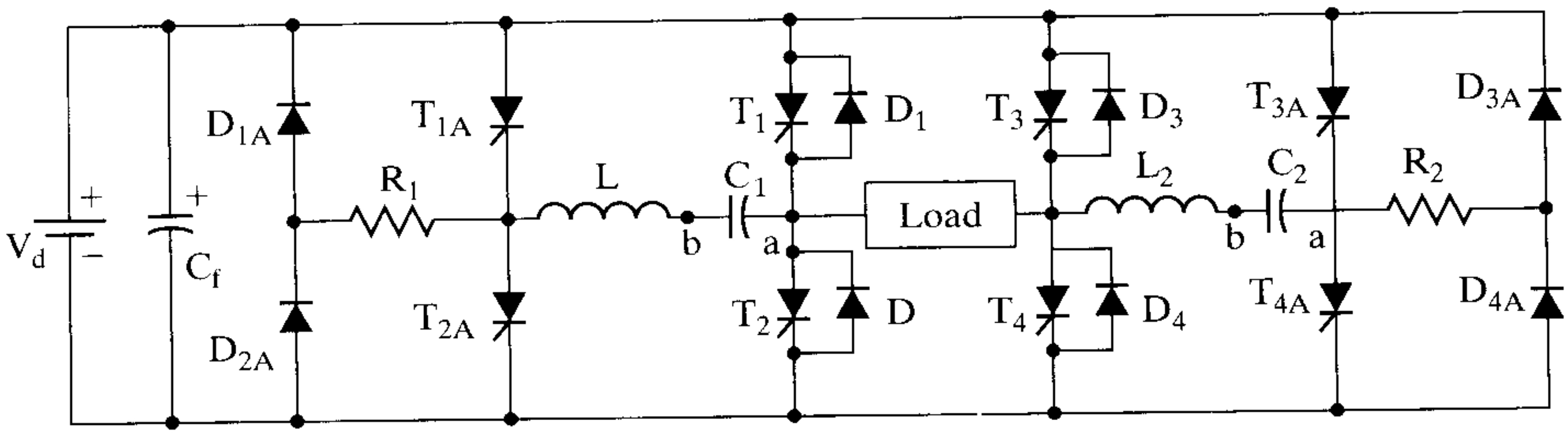

Figure 7.10 Full-bridge voltage-source inverter

• Voltage-source inverter with transistors

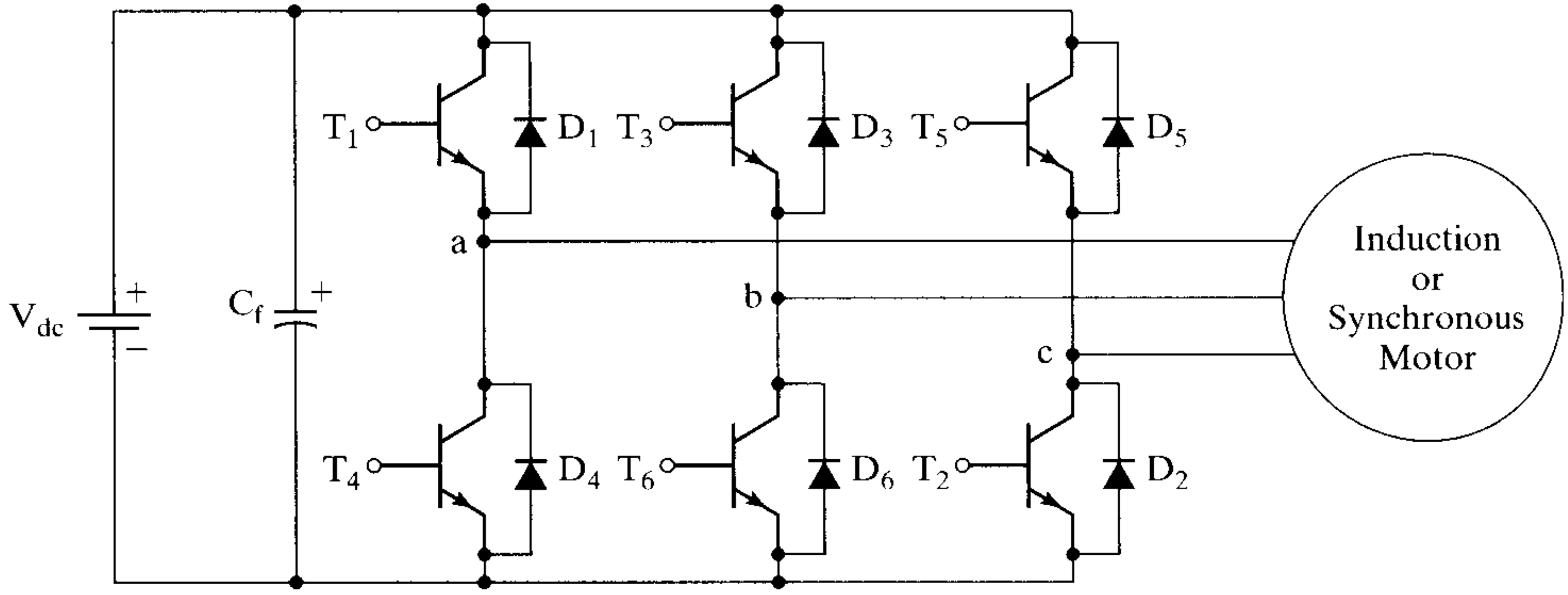

Figure 7.11 Voltage-source inverter with transistors

7.4 Voltage-source inverter

- A generic self-communicating inverter

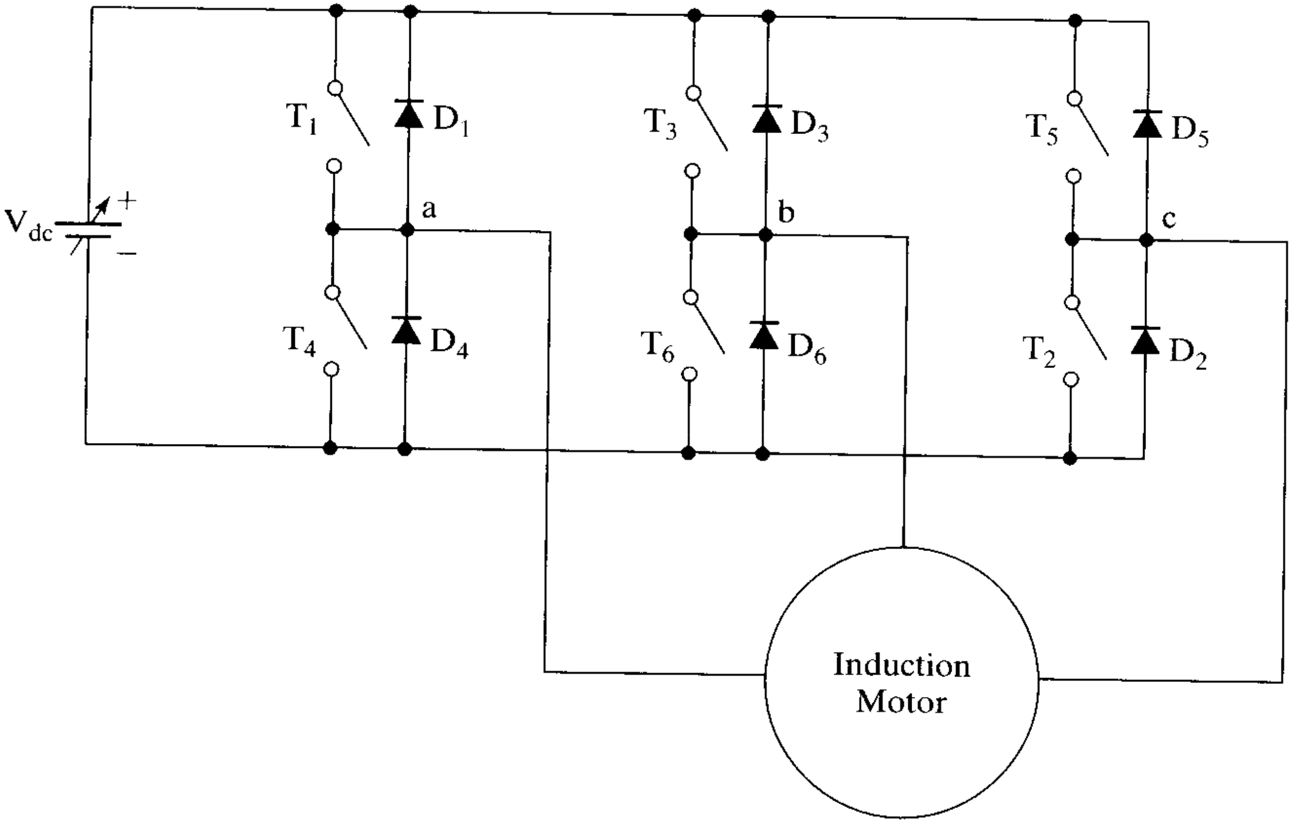

Figure 7.12 A schematic of the generic inverter-fed induction motor drive

- The gating signals and the line voltage

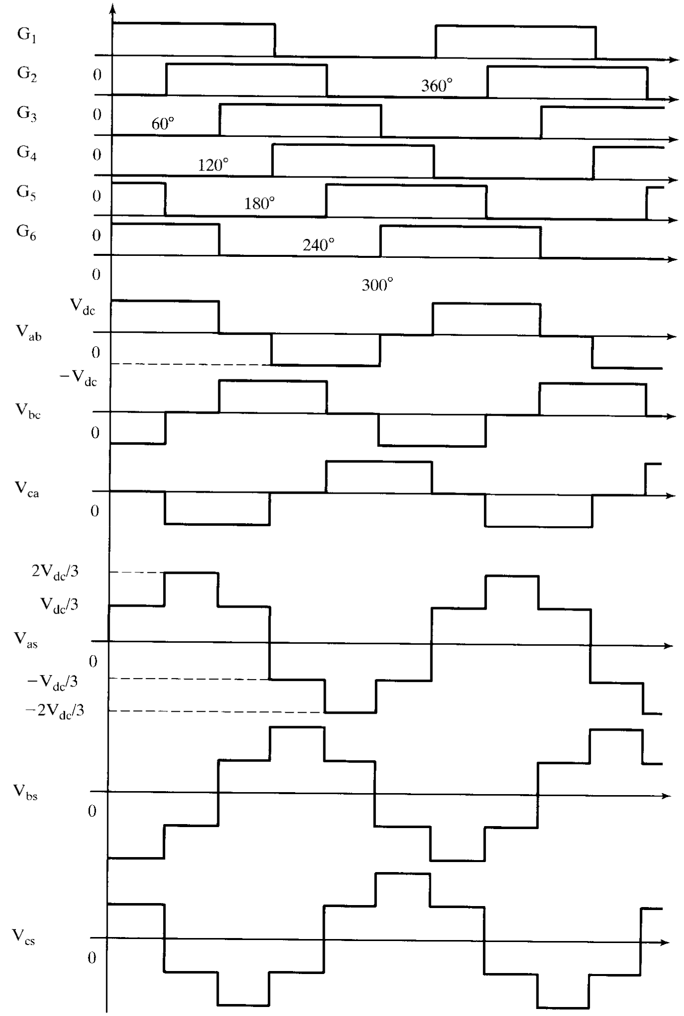

Figure 7.13 Inverter gate (base) signals and line- and phase-voltage waveforms

- The line voltage in term of the phase voltage

$V_{ab} = V_{as} - V_{bs}$

$V_{bc} = V_{bs} - V_{cs}$

$V_{ca} = V_{cs} - V_{as}$

- We can obtain

$V_{ab} - V_{ca} = 2V_{as} - (V_{bs} + V_{cs})$

- Because a three-phase system is balance,

$V_{as} + V_{bs} + V_{as} = 0.$

- Then, we have

$$V_{ab} - V_{ca} = 3V_{as}$$

- That is,

$$V_{as} = (V_{ab} - V_{ca})/3$$

- Similarly,

$$V_{bs} = (V_{bc} - V_{ab})/3$$

$$V_{cs} = (V_{ca} - V_{bc})/3$$

- These periodic voltage waveforms (in Fourier components) have the following

$$v_{ab}(t) = \frac{2\sqrt{3}}{\pi} v_{dc}(\sin\omega_s t - \frac{1}{5}\sin 5\omega_s t + \frac{1}{7}\sin 7\omega_s t - \ldots)$$

$$v_{bc}(t) = \frac{2\sqrt{3}}{\pi} v_{dc}\{\sin(\omega_s - 120^\circ)t - \frac{1}{5}\sin(5\omega_s - 120^\circ)t + \frac{1}{7}\sin(7\omega_s t - 120^\circ) - \ldots$$

$$v_{ca}(t) = \frac{2\sqrt{3}}{\pi} v_{dc}\{\sin(\omega_s + 120^\circ)t - \frac{1}{5}\sin(5\omega_s + 120^\circ)t + \frac{1}{7}\sin(7\omega_s t + 120^\circ) - \ldots$$

- The fundamental rms phase voltage for the six-stepped waveform is

$$V_{ph} = \frac{V_{as}}{\sqrt{2}} = \frac{2}{\pi}\cdot\frac{V_{dc}}{\sqrt{2}} = 0.45V_{dc}$$

- 7.4.2 Real power

$P_i = V_{dc}I_{dc} = 3V_{ph}I_{ph}\cos\phi_1$

$\Rightarrow I_{dc} = 1.35I_{ph}\cos\phi_1$

- 7.4.3 Reactive power

$Q_i = 3V_{ph}I_{ph}\sin\phi_1$

- 7.4.4 Speed control
- The air gap induced emf

$E_1 = 4.44k_{\omega 1}\phi_m f_s T_1$

- Neglecting the stator impedance, R_s+jX_{1s}

$$V_{ph} \cong E_1$$

- The flux is then written as

$$\phi_m \cong \frac{V_{ph}}{K_b f_s}$$

where $K_b = 4.44k_{\omega 1}T_1$

- If K_b is constant

$$\phi_m \propto \frac{V_{ph}}{f_s} \propto K_{vf}$$

- A number of control strategies about the voltage-to-frequency ratio:

(i) Constant volts/Hz control

(ii) Constant slip-speed control

(iii) Constant air gap flux control

(iv) Vector control

- 7.4.5 Constant volts/Hz control
- Relationship between voltage and frequency

$$V_{as1} = E_1 + I_{s1}(R_s + jX_{1s})$$

- Equivalent circuit of the induction motor

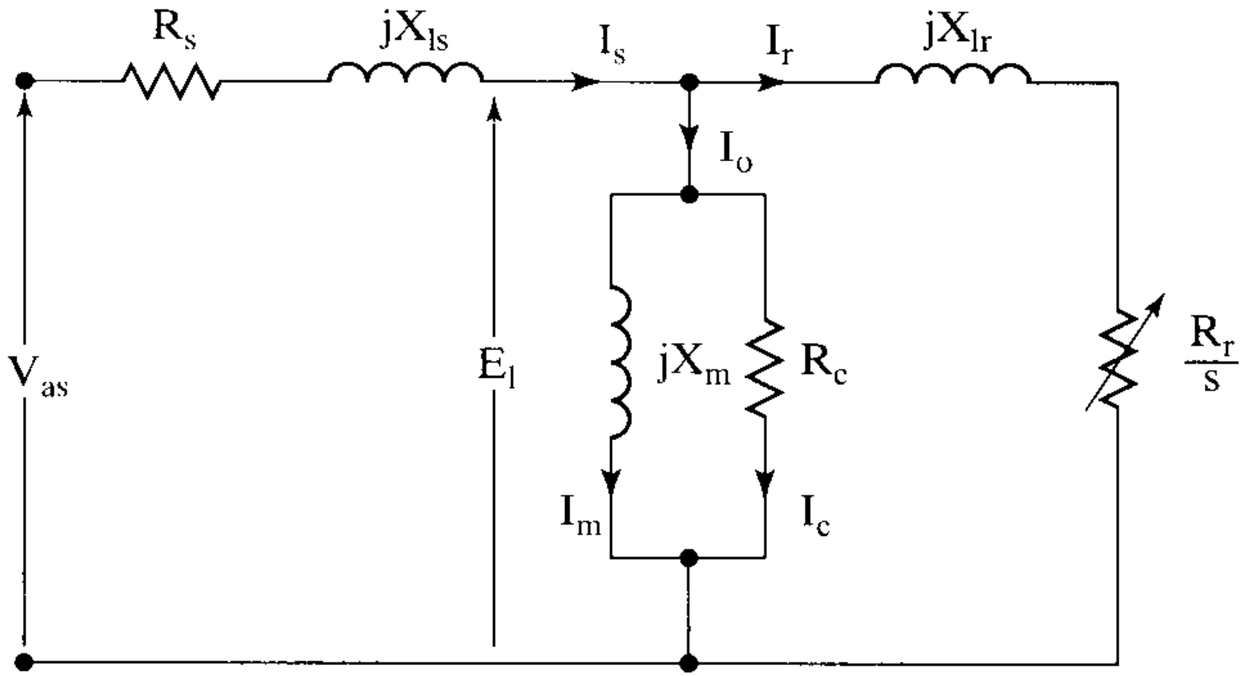

Figure 7.14 Equivalent circuit of the induction motor

- The phase voltage in p.u.

$V_{asn} = E_{1n} + I_{s1n}(R_{sn} + jX_{1sn})$

- The p.u. fundamental input voltage

$V_{asn} = I_{sn}R_{sn} + j\omega_{sn}(\lambda_{mn}+L_{1sn}I_{sn})$ (p.u.)

- The normalized input-phase stator voltage

$$V_{asn} = \sqrt{(I_{sn}R_{sn})^2 + \omega_{sn}^2(\lambda_{mn} + L_{1sn}I_{sn})^2} \quad \text{(p.u.)}$$

- The relationship between the applied phase voltage and frequency (for law performance)

$V_{as} = V_o + K_{vk}f_s$

where $V_o = I_{s1}R_s$

- Because of

$V_{as} = 0.24V_{dcn}$, $V_{on} = V_o/V_b$, and

$E_{1n} = E_1/V_b = K_{vf}f_s/K_{vf}f_b = f_{sn}$,

we have

$V_{dcn} = 2.22\{V_{on} + f_{sn}\}$

• Implementation of volts/Hz strategy

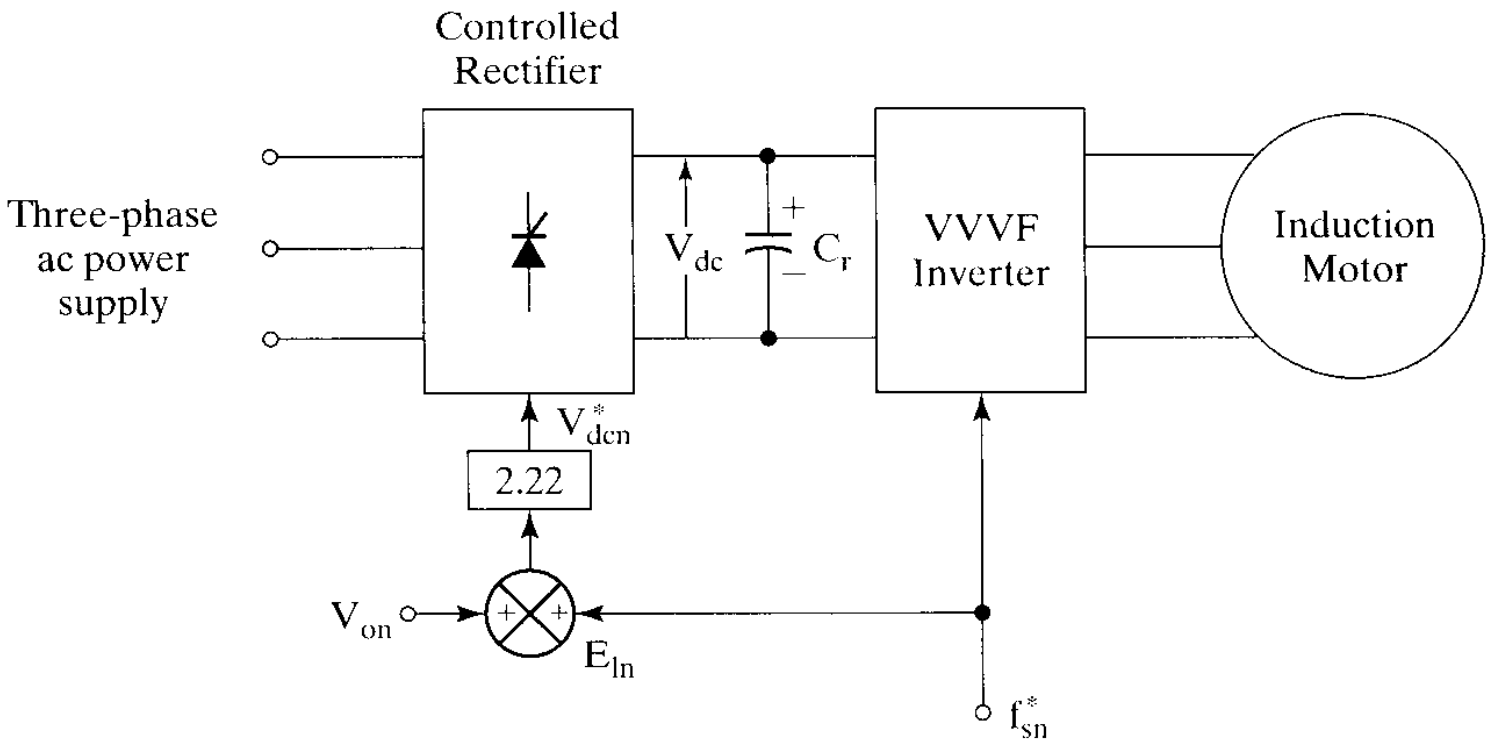

Figure 7.17 Implementation of volts/Hz strategy in inverter-fed induction motor drives

- Closed-loop induction motor drive constant volts/Hz control strategy

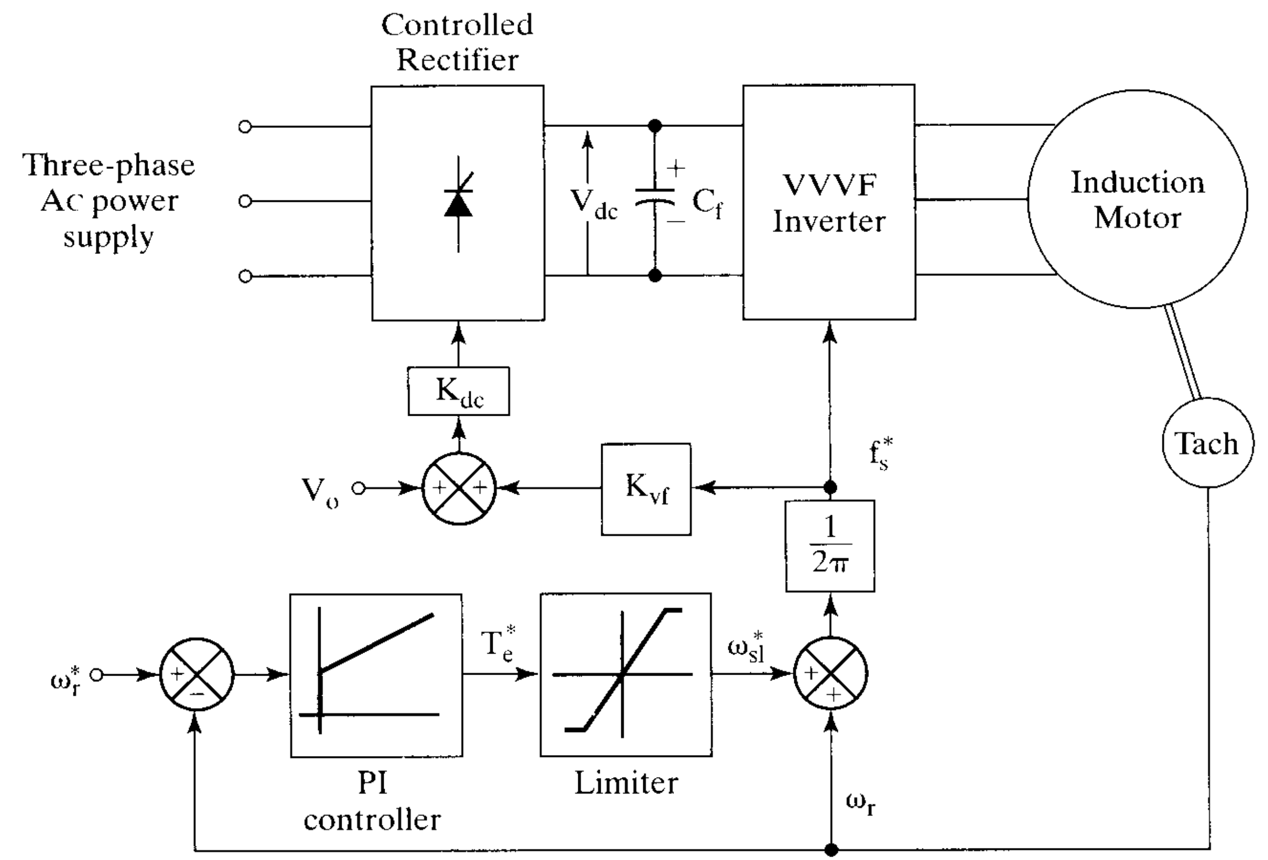

Figure 7.18 Closed-loop induction motor drive with constant volts/Hz control strategy

7.4.6 Constant slip-speed control

- Places the drive operation on the static torque-speed characteristic
- The speed of the induction motor

$$\omega_s = \omega_r + \omega_{s1}$$

- The slip is obtained as

$$s = \frac{\omega_{s1}}{\omega_s} = \frac{\omega_{s1}}{\omega_r + \omega_{s1}}$$

• Constant-slip-speed strategy(one-quadrant)

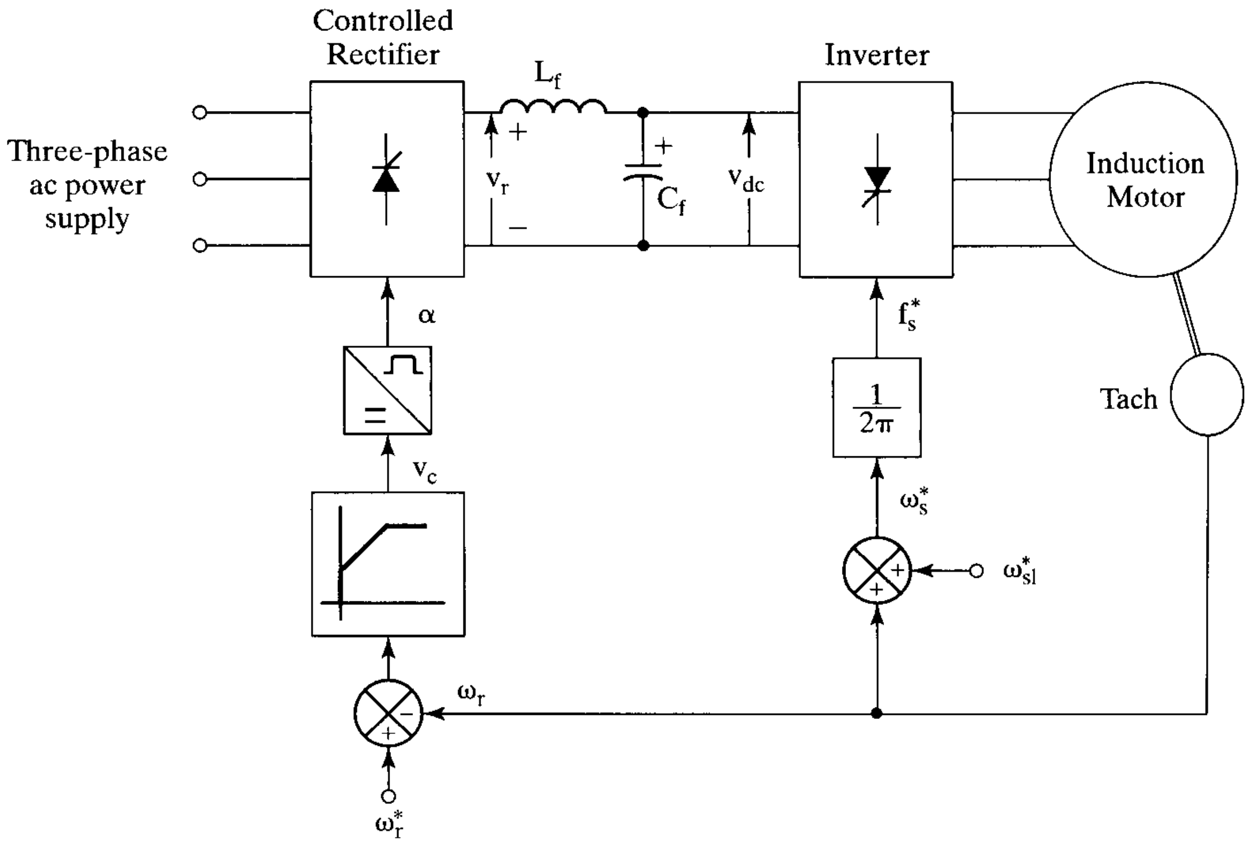

Figure 7.26 Constant-slip-speed drive strategy

- Simplified equivalent circuit considered for the steady state analysis

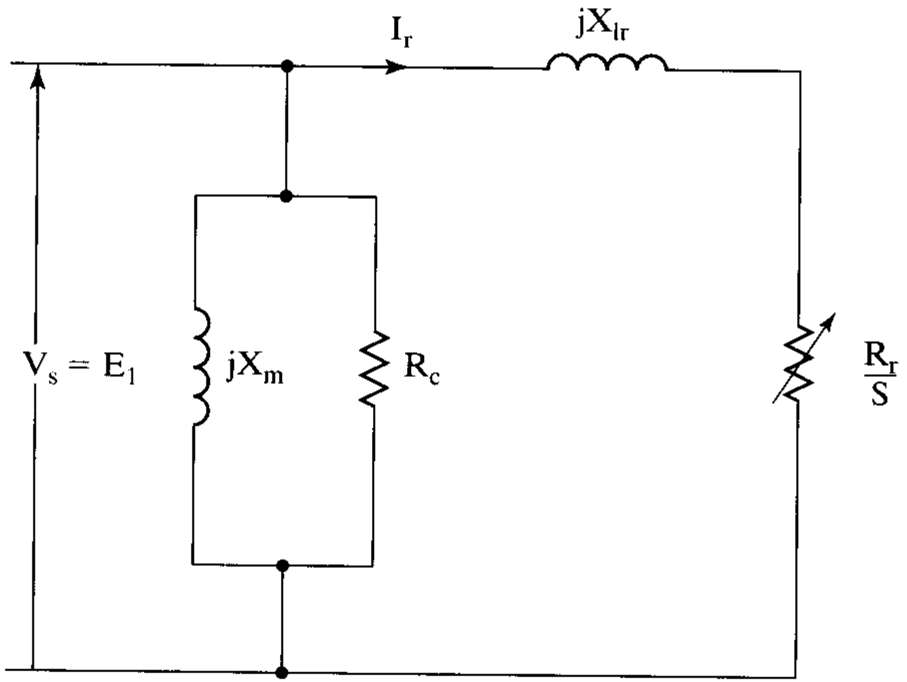

Figure 7.27 Simplified equivalent circuit considered for the steady-state analysis of the slip-controlled induction motor drive

- The rotor current

$$I_r = \frac{E_1}{(\frac{R_r}{s} + jX_{1r})} = \frac{E_1 / \omega_s}{(\frac{R_r}{\omega_{s1}} + jL_{1r})}$$

- The electromagnetic torque

$$T_e = \frac{P}{2} \cdot \frac{P_a}{\omega_s} = 3 \cdot \frac{P}{2} \cdot \frac{I_r^2 R_r}{s\omega_s} = 3 \cdot \frac{P}{2} \cdot \frac{I_r^2 R_r}{\omega_{s1}}$$

$$T_e = 3 \cdot \frac{P}{2} \cdot \frac{E_1^2}{\omega_s^2} \cdot \frac{(\frac{R_r}{\omega_{s1}})}{(\frac{R_r}{\omega_{s1}})^2 + (L_{1r})^2} = K_{tv}(\frac{E_1^2}{\omega_s^2}) \cong K_{tv}(\frac{V_s}{\omega_s})^2$$

$$K_{tv} = \frac{3\frac{P}{2}(\frac{R_r}{\omega_{s1}})}{(\frac{R_r}{\omega_{s1}})^2 + (L_{1r})^2}$$

- Torque vs. applied voltage for various slip speed

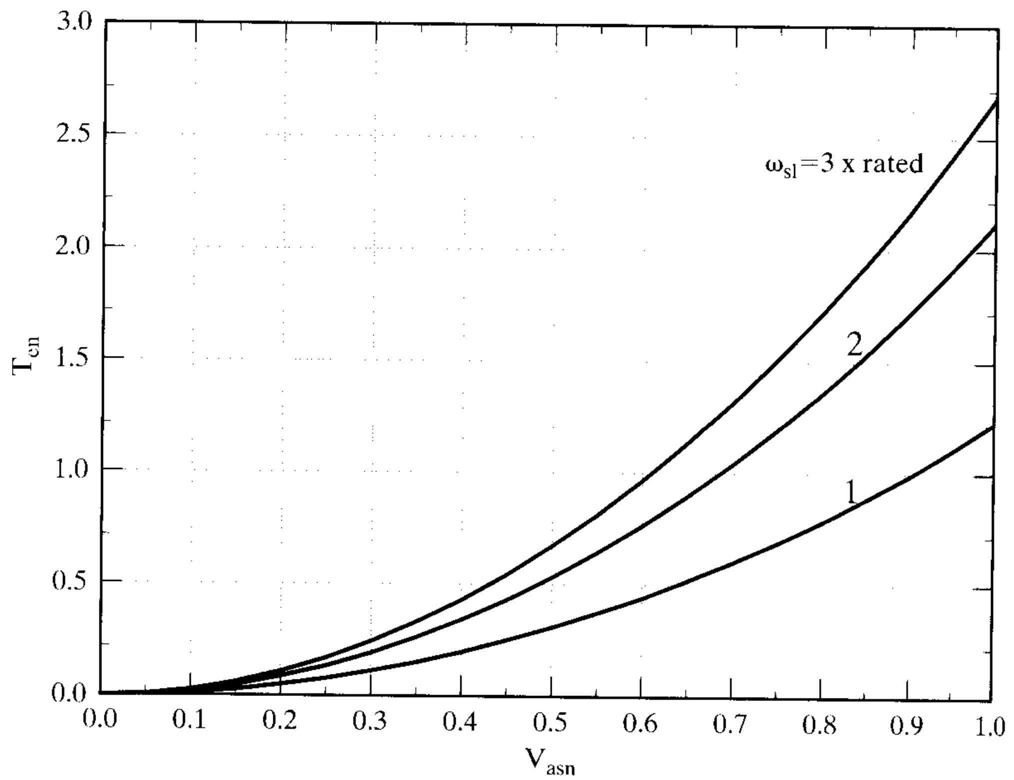

Figure 7.28 Torque vs. applied voltage for various slip speeds at rated stator frequency in p.u.

- 7.4.7 Constant air gap flux control
- Equivalent separately-excited dc motor in terms of its speed but not in terms of decoupling of flux and torque channel.
- Constant air gar flux linkages

$$\lambda_m = L_m i_m = \frac{E_1}{\omega_s}$$

- The electromagnetic torque

$$T_e = 3 \cdot \frac{P}{2} \cdot \lambda_m^2 \cdot \frac{(\frac{R_r}{\omega_{s1}})}{(\frac{R_r}{\omega_{s1}})^2 + (L_{1r})^2} = K_{tm} \frac{(\frac{R_r}{\omega_{s1}})}{(\frac{R_r}{\omega_{s1}})^2 + (L_{1r})^2}$$

- Drive strategy for constant-air gap-flux-controlled induction motor drive

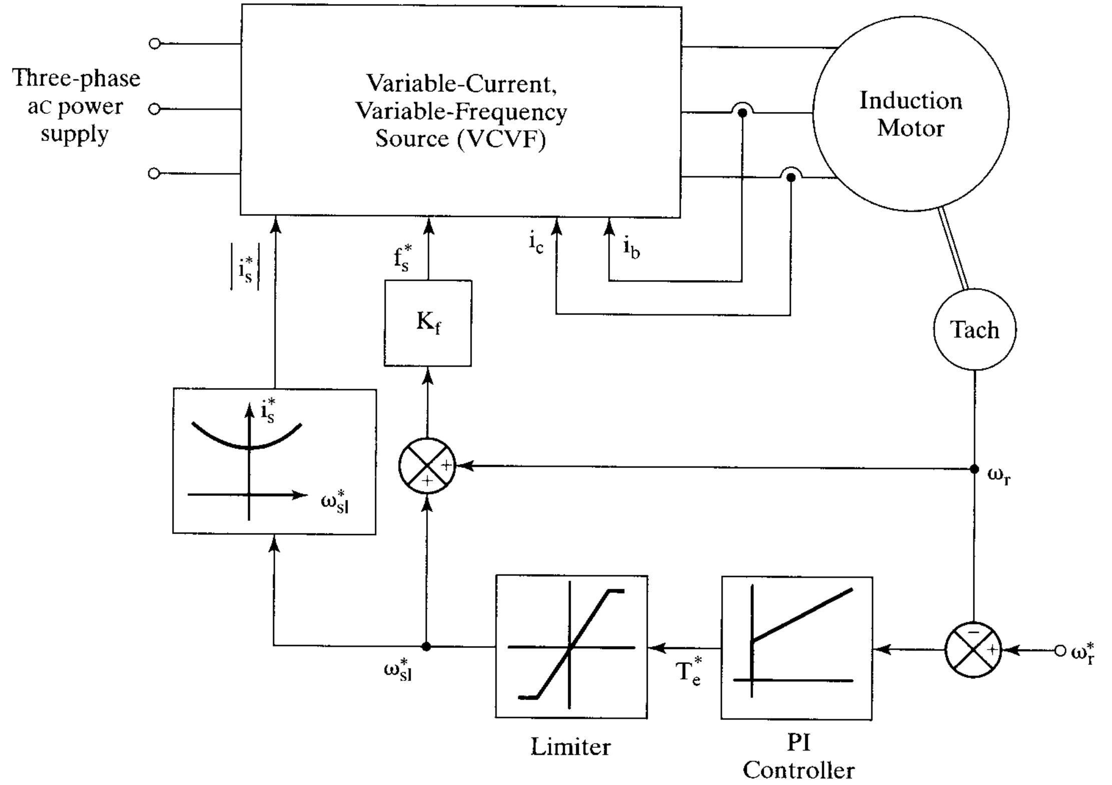

Figure 7.30 Drive strategy for constant-air gap-flux-controlled induction motor drive

- 9.4.7 Control of harmonics
- Sinusoidal pulse-width modulation

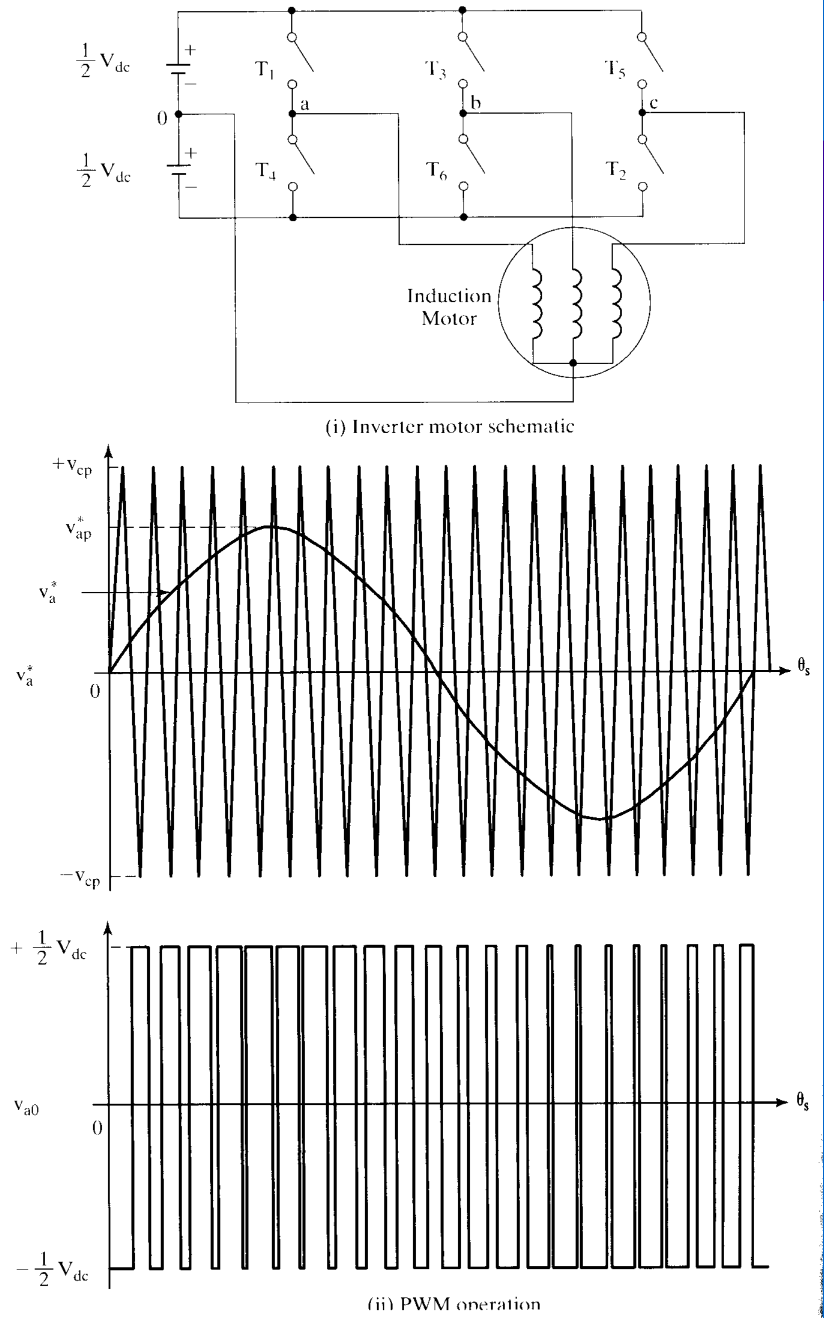

Figure 7.37 Sinusoidal pulse-width modulation

- The switching logic for one phase

$$v_{a0} = \frac{1}{2} V_{dc}, \quad v_c < v_a^*$$
$$= -\frac{1}{2} V_{dc}, \quad v_c > v_a^*$$

- The fundamental of this midpoint voltage

$$v_{a01} = \frac{V_{dc}}{2} \cdot \frac{v_{ap}^*}{v_{cp}}$$

- 7.4.10 Steady-state evaluation with PWM voltage
- PWM voltage generation

$$t(i) = \frac{1 \pm m \sin[a(i)]}{2f_c}, \quad + \text{for even n; - for odd n}$$

$$a(i) = \frac{2\pi i}{n}, \text{ rad;}$$

where n is the ratio between the carrier and modulation frequencies, t(i) is ith pulse width, m is the modulation ration, fc is the carrier frequency.

- The pulse widths in electrical radians

  $p_w(i) = t(i) f_s$, rad

  where fs is the modulation frequency.
- (see the table on pp. 370)
- The d and q axes voltages

$$v_{qs} = \frac{2}{3}[v_{as} - 0.5(v_{bs} + v_{cs})]$$

$$v_{ds} = \frac{1}{\sqrt{3}}[(v_{cs} - v_{bs})]$$

- The model in the stator reference frames

$$V = (R+Lp)i + G\omega_r i$$

$$V = [v_{as} \;\; v_{ds} \;\; 0 \;\; 0]^t$$

$$i = [i_{qs} \;\; i_{ds} \;\; i_{qr} \;\; i_{dr}]^t$$

$$R = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix} \qquad L = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & R_r & 0 \\ 0 & L_m & 0 & R_r \end{bmatrix}$$

$$G = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & L_m & 0 & -L_r \\ -L_m & 0 & L_r & 0 \end{bmatrix}$$

- State-space form

$$\dot{X} = AX + Bu$$

where $A = -L^{-1}[R+\omega_r G]$

$B = L^{-1}$

$X = i$

$u = V$

- Direct evaluation of steady-state current
- The solution of current vector

$$X(t) = e^{At}X(0) + \int_0^t e^{A(t-\tau)}Bu(\tau)d\tau$$

- Discretization

$$X(T_s) = e^{AT_s}X(0) + (e^{AT_s} - I)A^{-1}Bu(0)$$

- The k^{th} sampling interval

$X(k+1) = \Phi X(k) + Fu(k)$

where $\Phi = e^{AT_s}$ and $F = (\Phi - I)A^{-1}B$

- X(k+1) = X(0) (if k+1 = 360 electrical degrees)
- The steady-state initial vector

$$X(0) = [I - \Phi^{(k+1)}]^{-1}\{\sum_{j=0...k} \Phi^{j} F u(k-j)\}$$

- Steady-state performance

$$T_e(k) = \frac{3}{2}\frac{P}{2} L_m\{i_{qs}(k) i_{ds}(k) - i_{ds}(k) i_{qr}(k)\}$$

$$i_{as}(k) = i_{qs}(k)$$

$$i_{bs}(k) = -0.5 i_{qs}(k) - 0.866 i_{ds}(k)$$

7.5 Current-source ...

- Torque is directly related to the current rather than voltage.
- 7.5.2 ACSI (Autosequentially commutated Current-source Inverter)
- The inductor is provided to maintain the dc link current at a steady value.

• Current-source induction motor drive

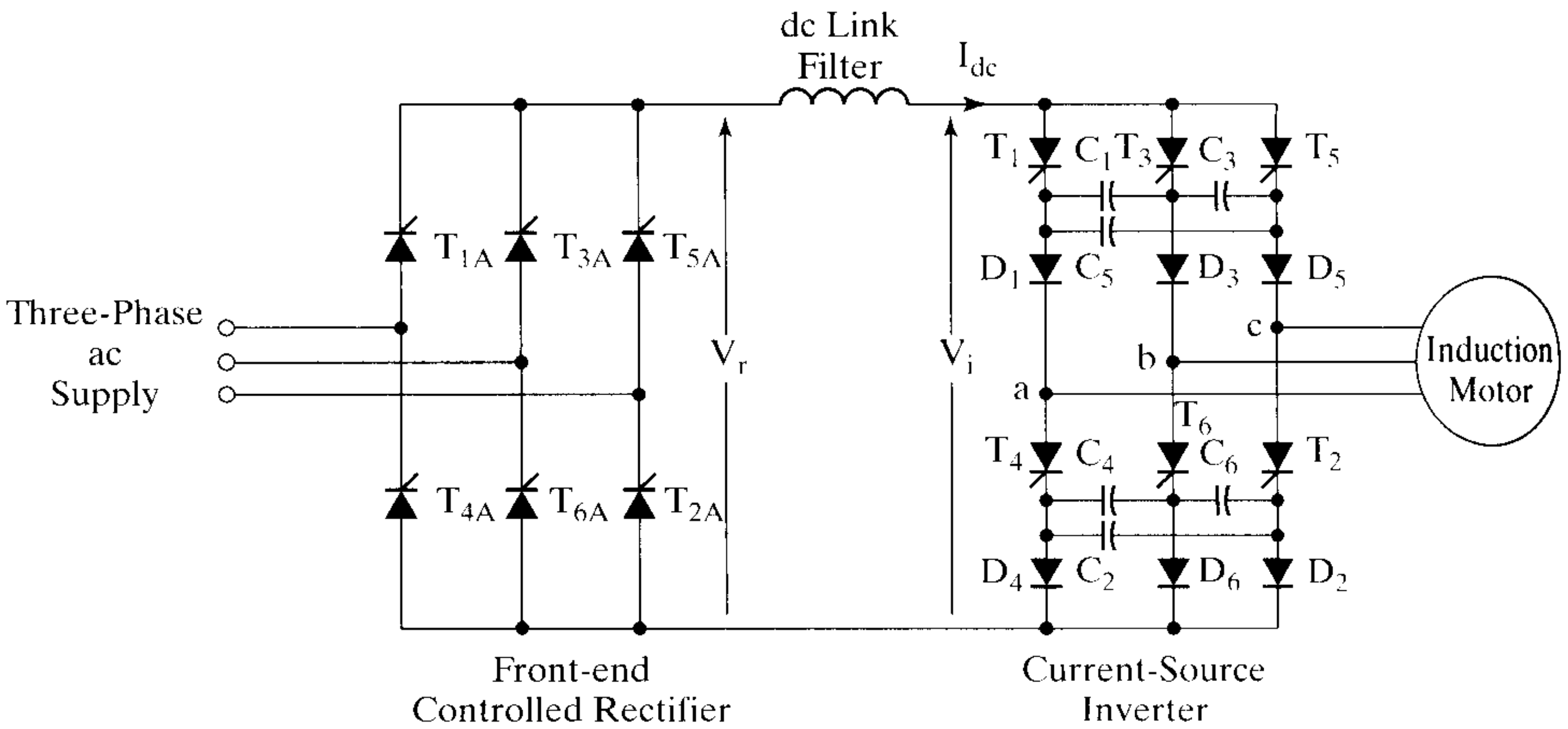

Figure 7.44 Current-source induction motor drive

• Commutation

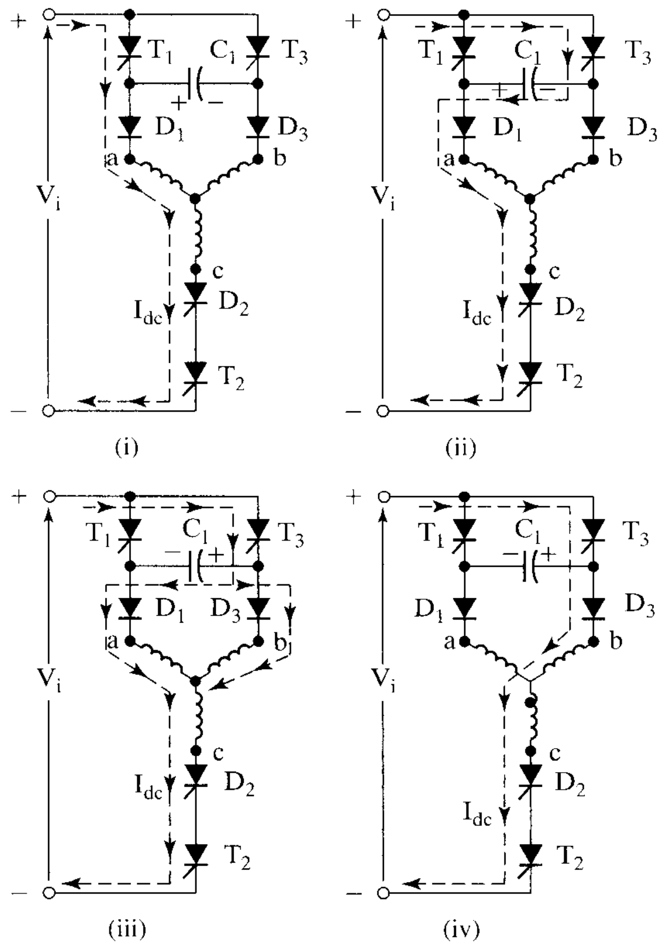

Figure 7.45 Commutation sequence in an autosequentially commutated current-source inverter

- Stator current in a star connection

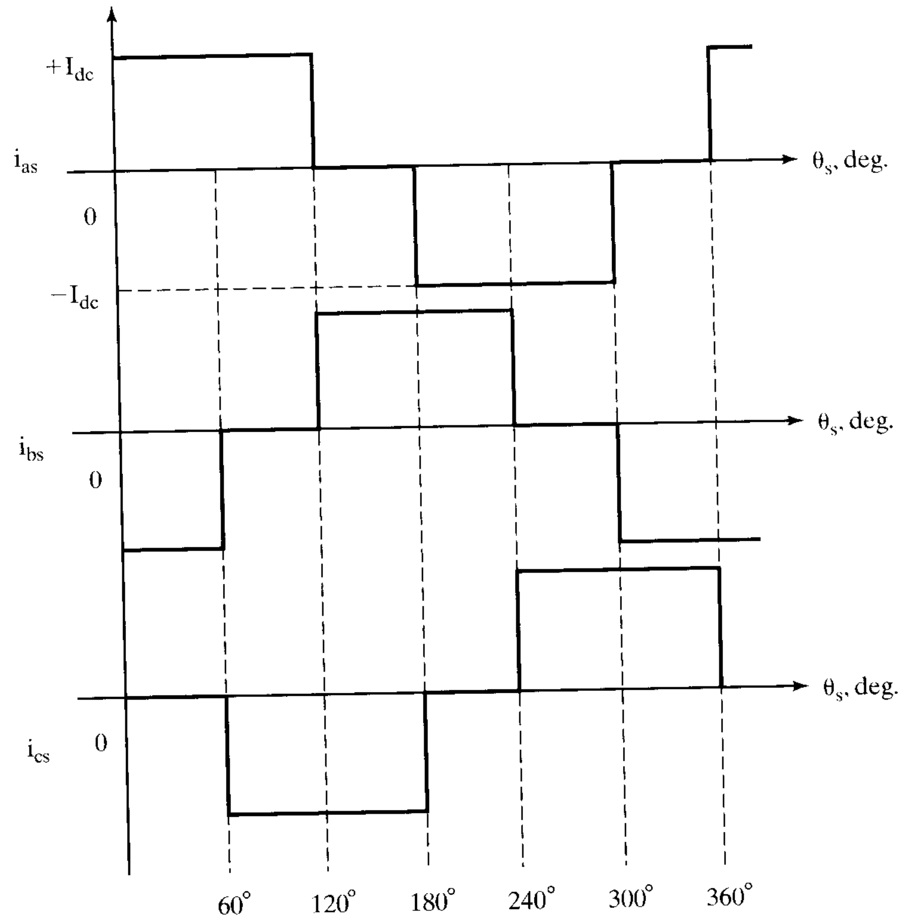

Figure 7.46 Stator currents in a star-connected induction motor fed from a current source

• Forward motoring

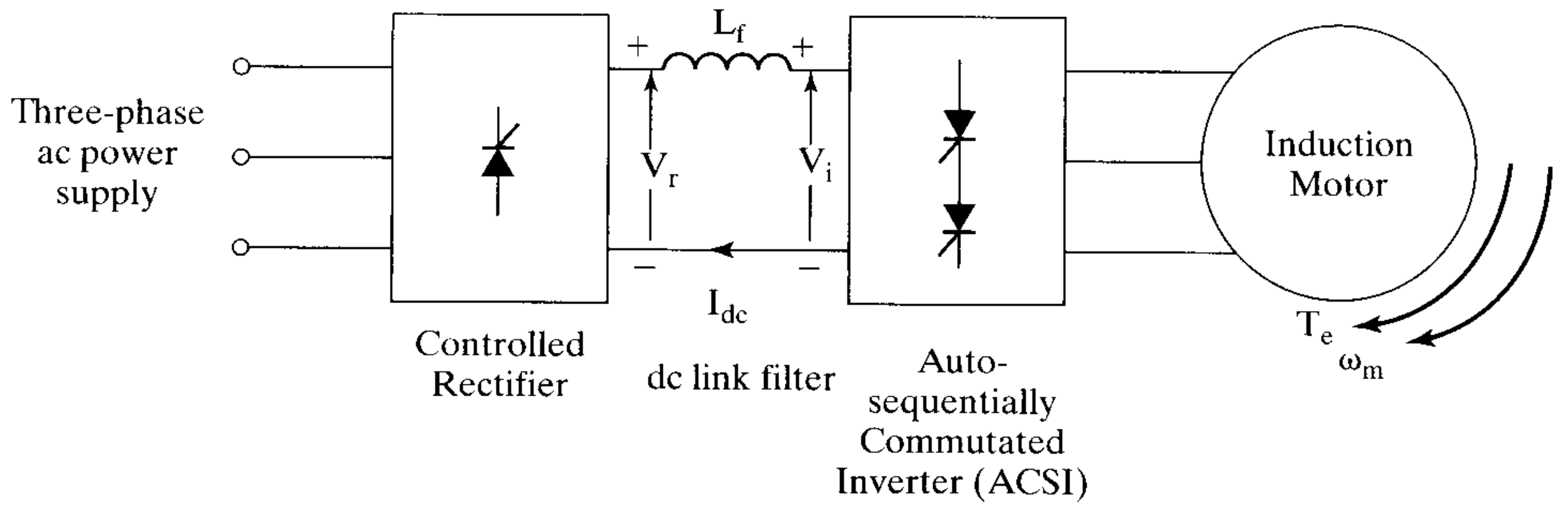

Figure 7.47 Forward motoring of the current-source induction motor drive

• Regeneration

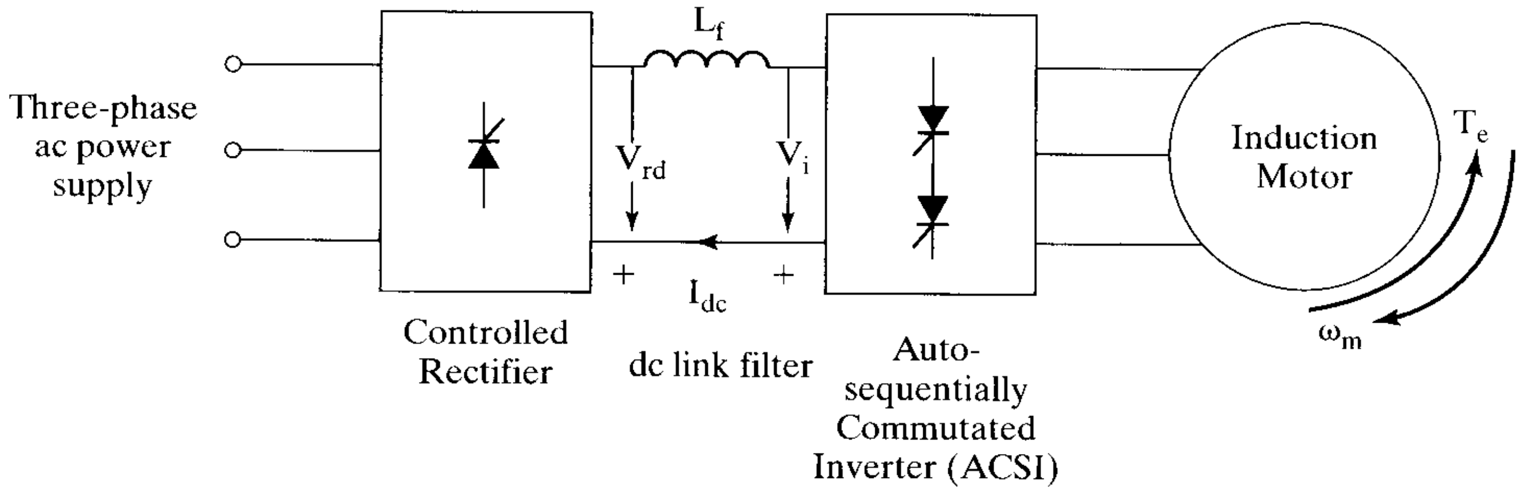

Figure 7.48 Regeneration in the current-source induction motor drive

- 7.5.3 Steady-state performance
- Equivalent circuit approach

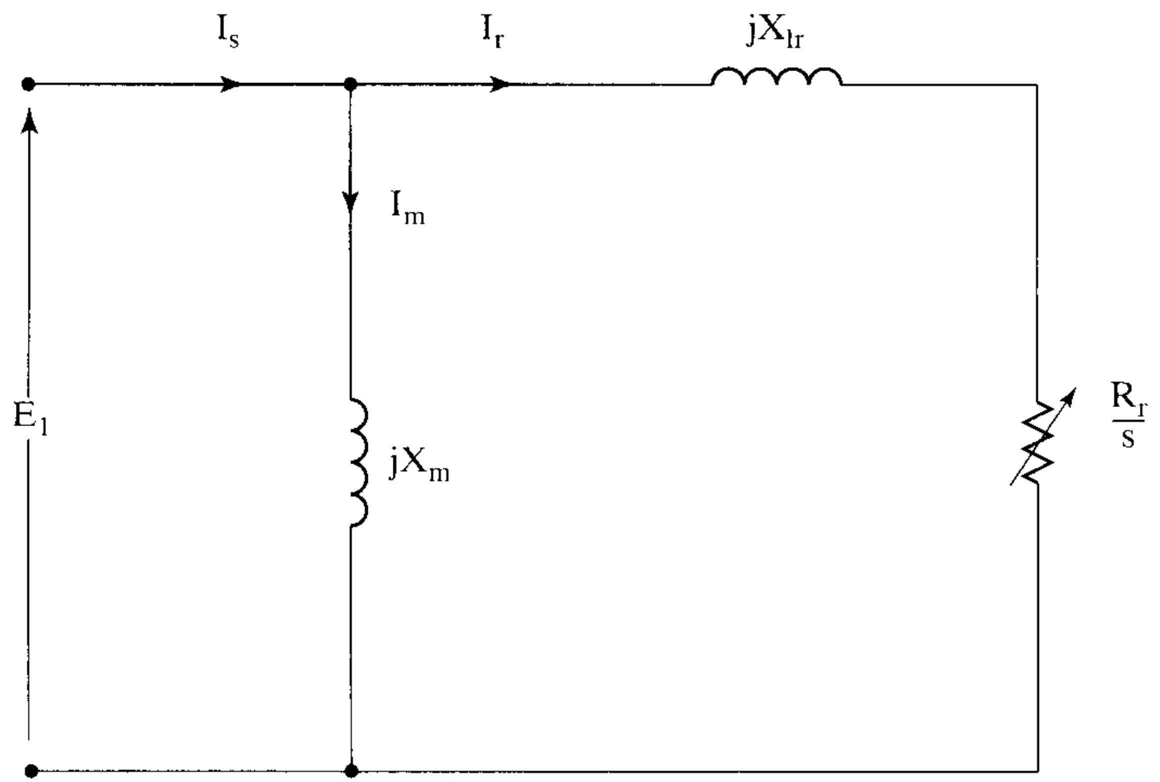

Figure 7.49 Induction-motor equivalent circuit with constant stator current

- The rotor and magnetizing currents

$$I_r = \frac{jL_m}{\frac{R_r}{s\omega_s} + jL_r} \cdot I_s$$

$$I_m = \frac{\frac{R_r}{s\omega_s} + jL_{1r}}{\frac{R_r}{s\omega_s} + jL_r} \cdot I_s$$

where $I_s \frac{\sqrt{2}\sqrt{3}}{\pi} I_{dc} = 0.779 I_{dc}$

- The electromagnetic torque

$$T_e = 3 \cdot \frac{P}{2} \cdot \frac{L_m^2}{(\frac{R_r}{s\omega_s})^2 + L_r^2} \cdot \frac{R_r}{s\omega_s} \cdot I_s^2$$

- The maximum torque occurs at

$s = R_r/\omega_s L_r$

- Thus

$$T_{e(max)} = \frac{3}{2}\cdot\frac{P}{2}\cdot\frac{L_m^2}{(\frac{R_r}{s\omega_s})}\cdot I_s^2 = \frac{3}{2}\cdot\frac{P}{2}\cdot\frac{L_m^2}{L_r}\cdot I_s^2$$

- 7.5.4 Direct steady-state evaluation of six-step current-source inverter-fed induction motor (CSIM) drive system

- Stator currents:

(i) interval I: $0<\theta_s<60^0$

$i_{as} = I_{dc}; \quad i_{bs} = -I_{dc}; \quad i_{cs} = 0.$

The quadrature axis stator current

$$i_{qs}^e = \frac{2}{3}[i_{as}\cos\theta_s + i_{bs}\cos(\theta_s - \frac{2\pi}{3}) + i_{cs}\cos(\theta_s + \frac{2\pi}{3})]$$

$$i_{qsI}^e = aI_{dc}\cos(\theta_s + \frac{\pi}{6}) \quad \text{where} \quad a = \frac{2}{\sqrt{3}}$$

similarly,

$$i_{dsI}^e = aI_{dc}\sin(\theta_s + \frac{\pi}{6})$$

(ii) interval II: $60^{\circ}<\theta_s<120^{\circ}$

The quadrature and driect asix stator currents

$$i^e_{qsII} = aI_{dc}\cos(\theta_s - \frac{\pi}{6}) = aI_{dc}\cos(\theta_s + \frac{\pi}{6} - \frac{\pi}{3}) = \frac{1}{2} i^e_{qsI} + \frac{\sqrt{3}}{2} i^e_{dsI}$$

$$i^e_{dsII} = aI_{dc}\sin(\theta_s - \frac{\pi}{6}) = aI_{dc}\sin(\theta_s + \frac{\pi}{6} - \frac{\pi}{3}) = -\frac{\sqrt{3}}{2} i^e_{qsI} + \frac{1}{2} i^e_{dsI}$$

- The transformation matrix

$$\begin{bmatrix} i^e_{qs}(\theta_s + \frac{\pi}{3}) \\ i^e_{ds}(\theta_s + \frac{\pi}{3}) \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{\sqrt{3}}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i^e_{qs}(\theta_s) \\ i^e_{ds}(\theta_s) \end{bmatrix}$$

• Closed-loop system

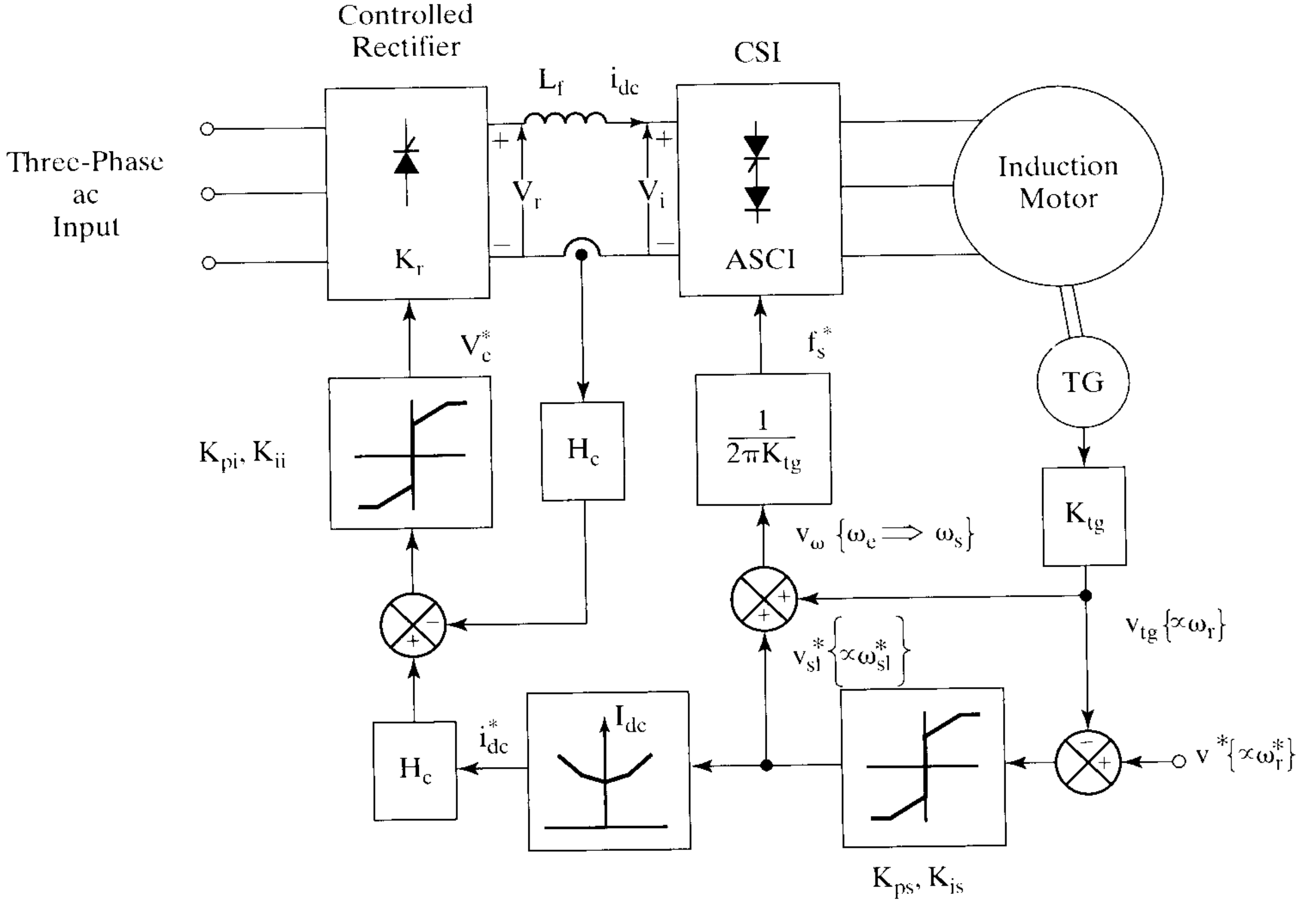

Figure 7.52 CSIM drive system with speed control