Power Electronics

Chap. 13

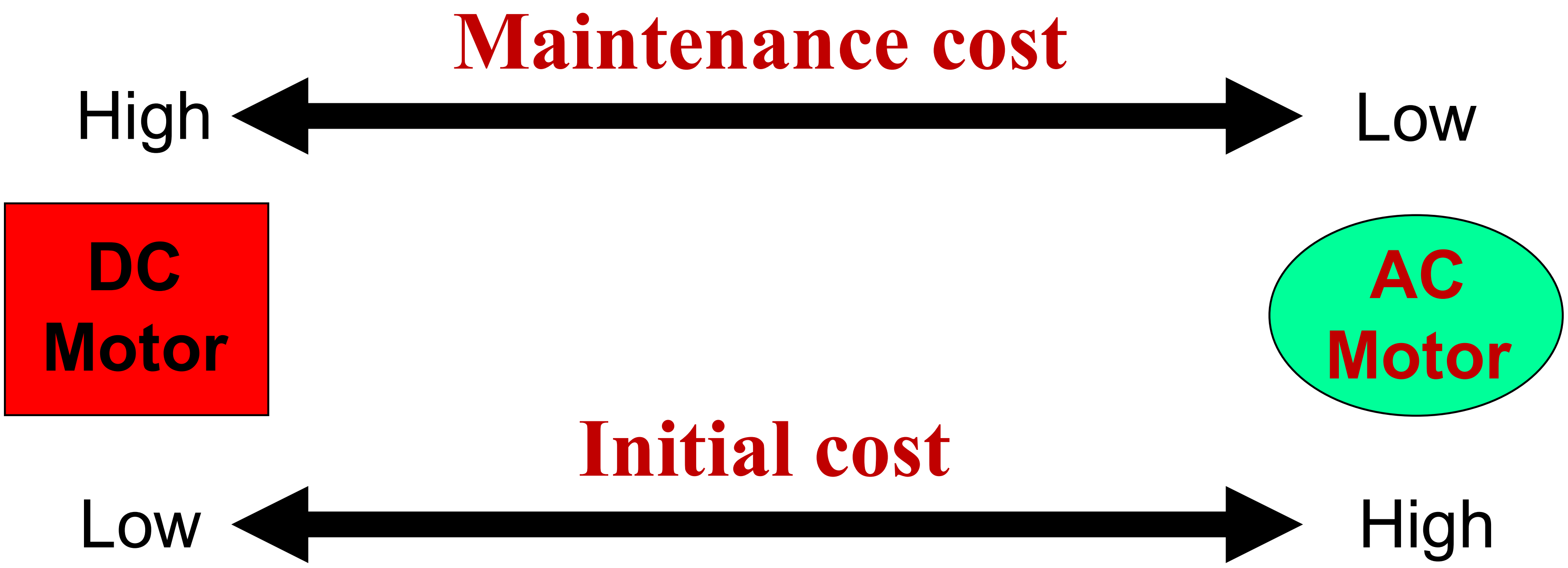
DC Motor Drives

Outlines

- Introduction
- Equivalent Circuit of DC Motors
- Permanent-magnet DC Motors
- DC Motors with A Separately Excited Field Winding
- DC Servo Drives
- Adjustable-speed DC Drives
- Summary

Introduction

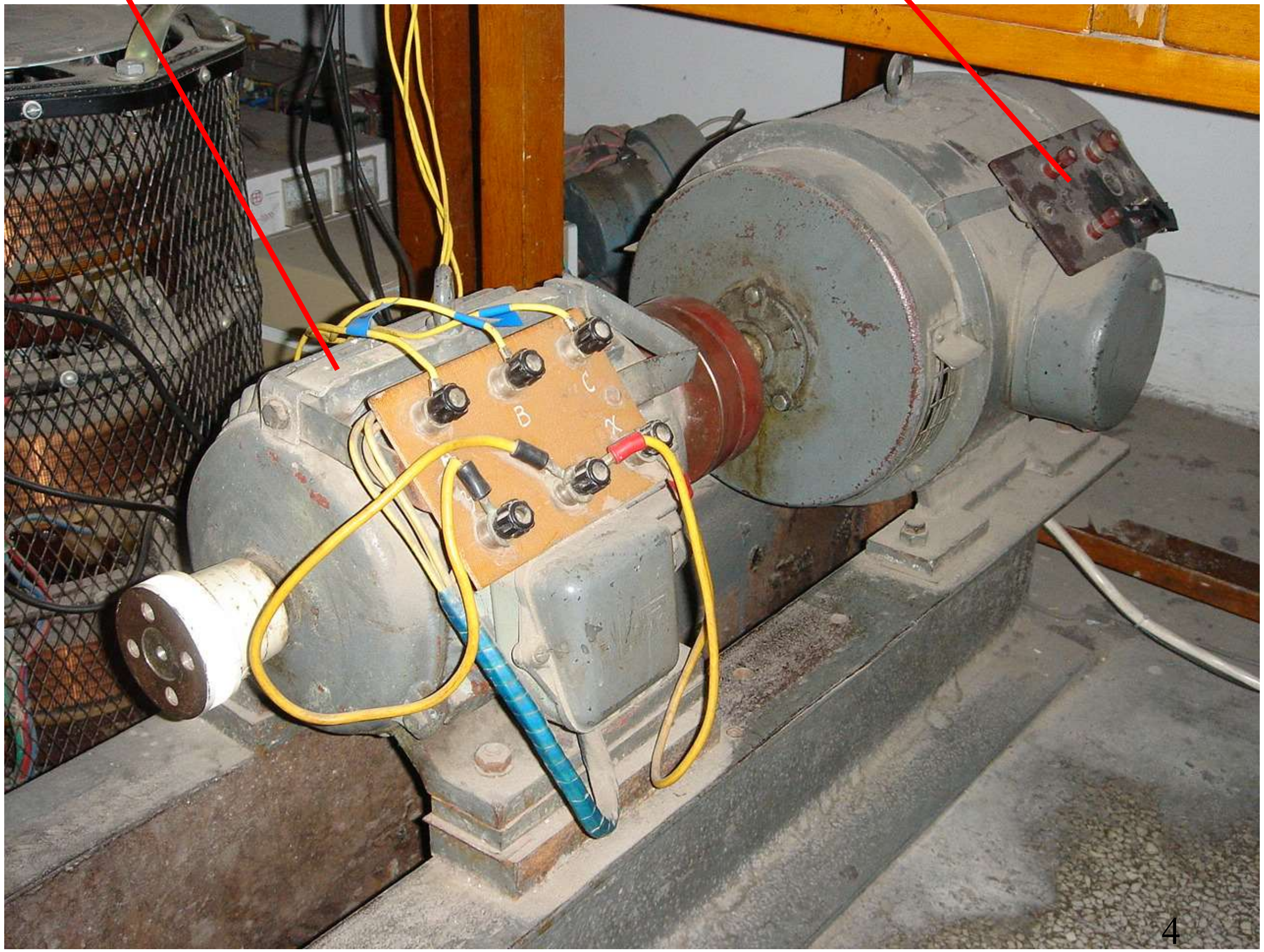
- In the past few years, the use of ac motor drives in the speed and position control applications is increasing due to their simple structure, low maintenance, high reliability, high efficiency, and high power density.



Introduction

Induction Motor

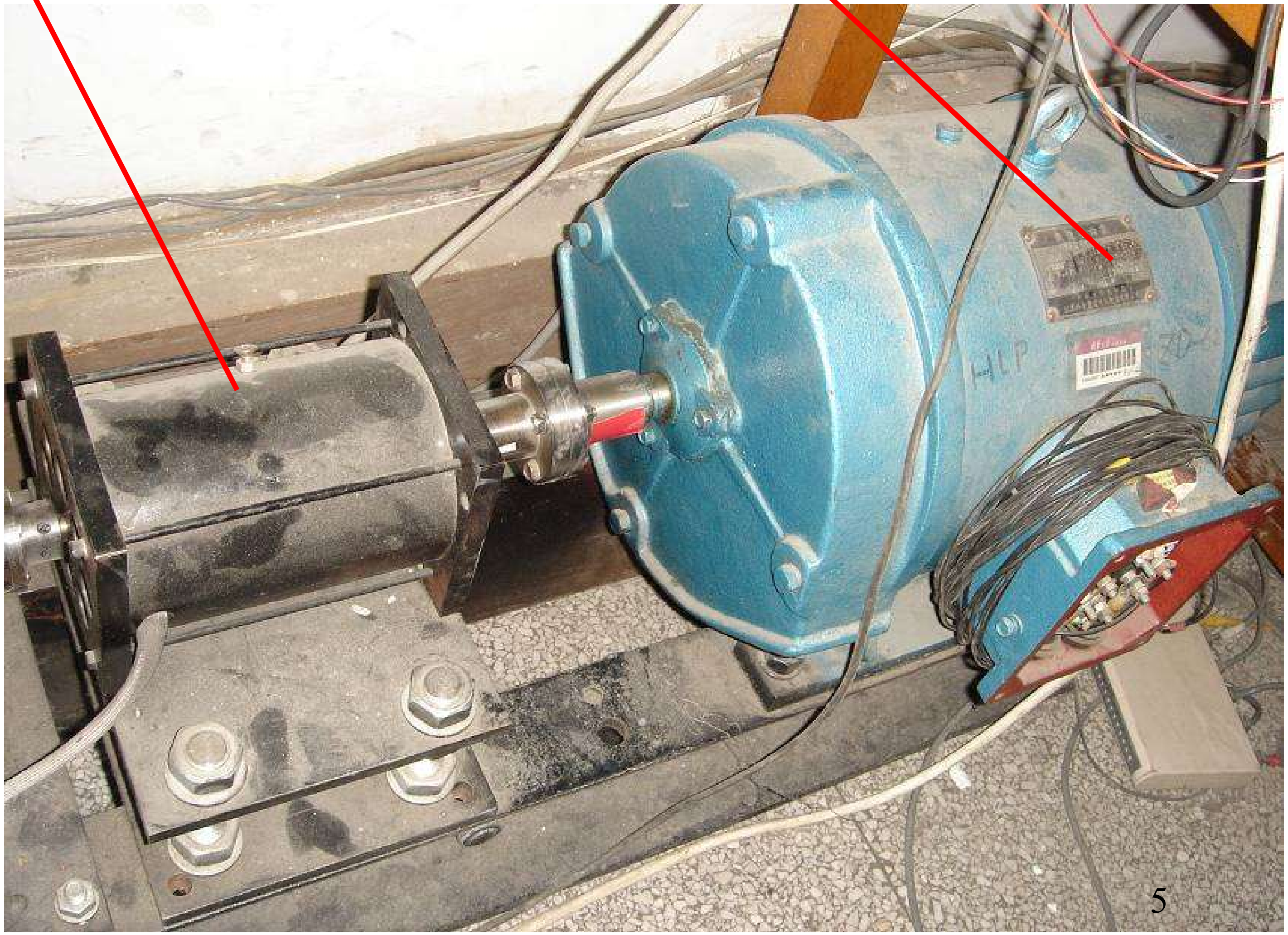
DC Machine



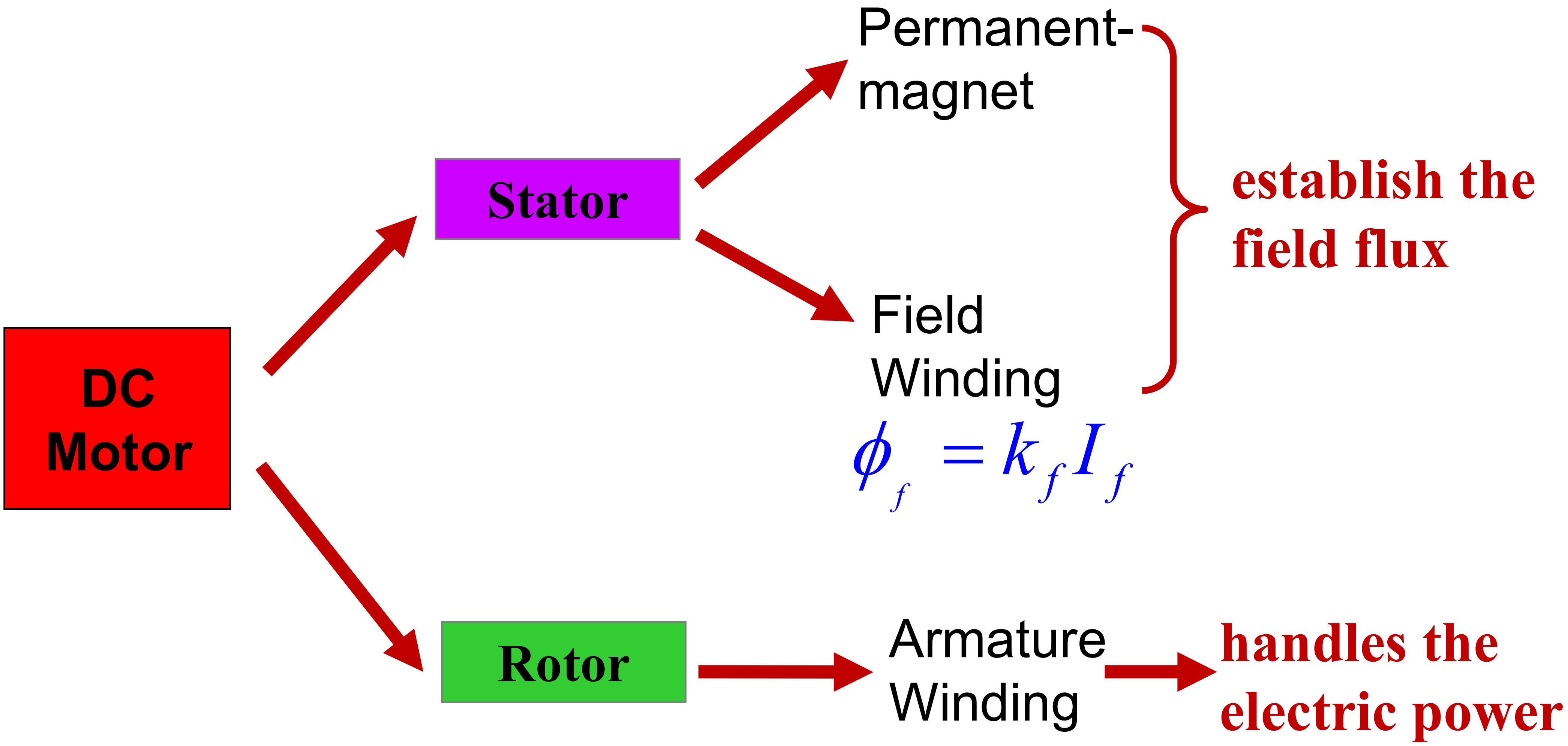
Introduction

IPMSM

DC Machine



Equivalent Circuit of DC Motors



Equivalent Circuit of DC Motors

Permanent-magnet **With field winding** $\phi_f = k_f I_f$

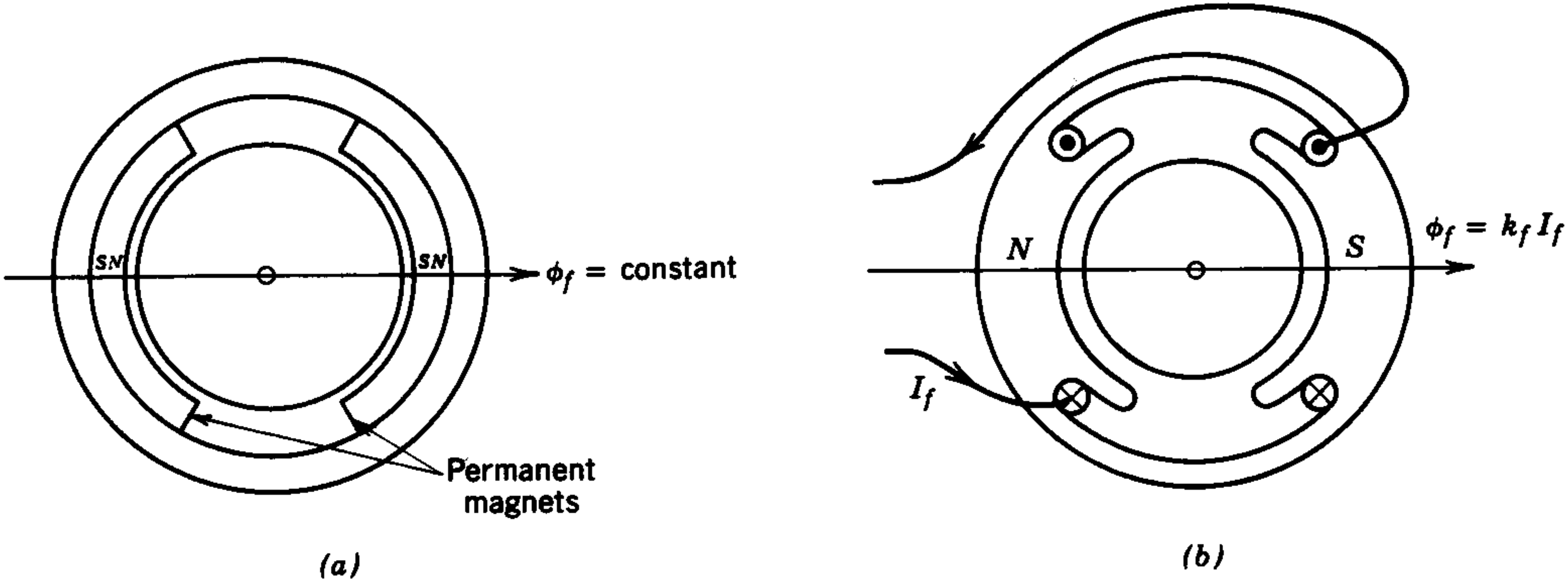


Figure 13-1 A dc motor: (*a*) permanent-magnet motor; (*b*) dc motor with a field winding.

Equivalent Circuit of DC Motors

- The electromagnetic torque is produced by the interaction between the field flux and the armature current.

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

- A back-emf is produced by the rotation of armature conductors at a speed in the presence of a field flux.

$$e_a = k_e \phi_f \omega_m$$

Electrical Power

$$P_e = e_a i_a = k_e \phi_f \omega_m i_a$$

Mechanical Power

$$P_m = \omega_m T_{\mathrm{em}} = k_t \phi_f \omega_m i_a$$

- In steady state, $P_e = P_m$

$$k_t \left[\frac{\mathrm{Nm}}{\mathrm{A \cdot Wb}} \right] = k_e \left[\frac{\mathrm{V}}{\mathrm{Wb \cdot rad/s}} \right]$$

Equivalent Circuit of DC Motors

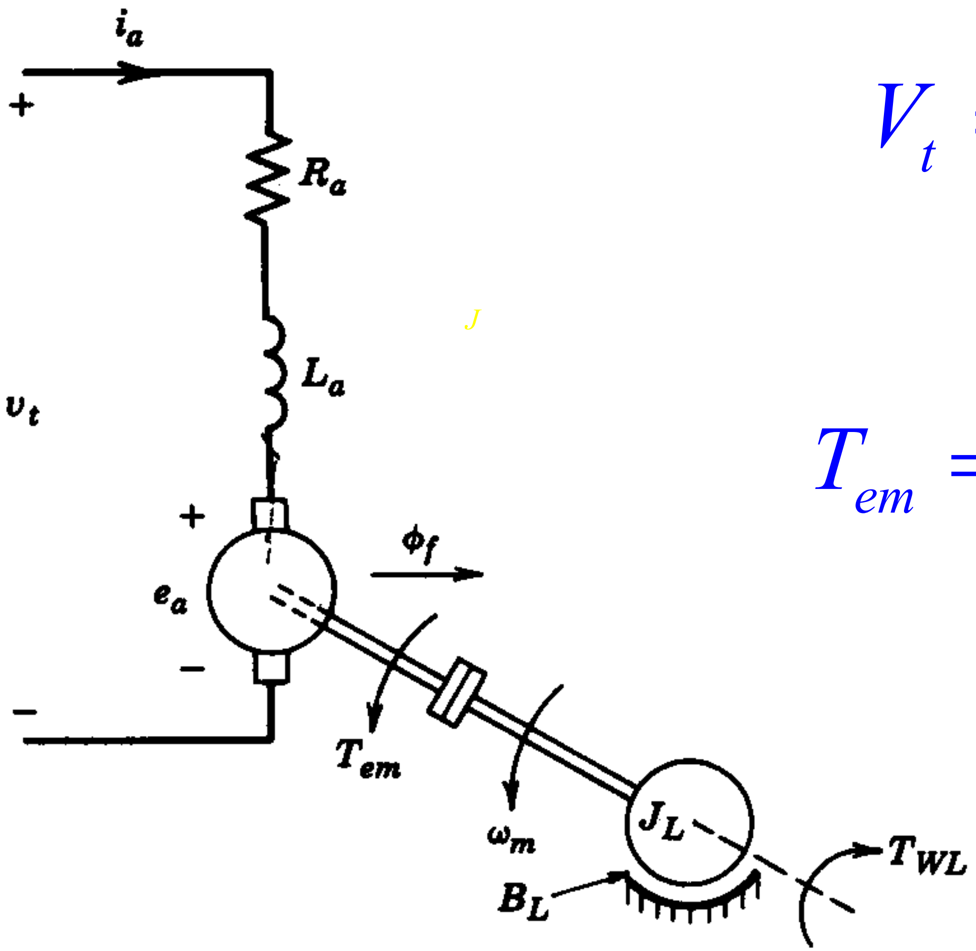


Figure 13-2 A dc motor equivalent circuit.

$$V_t = e_a + R_a i_a + L_a \frac{di_a}{dt}$$

$$T_{em} = J \frac{d\omega_m}{dt} + B\omega_m + T_{WL}(t)$$

Total equivalent inertia J

Total equivalent damping B

Equivalent load torque T_{WL}

Equivalent Circuit of DC Motors

$$T_{em} = k_t \phi_f i_a \qquad e_a = k_e \phi_f \omega_m$$

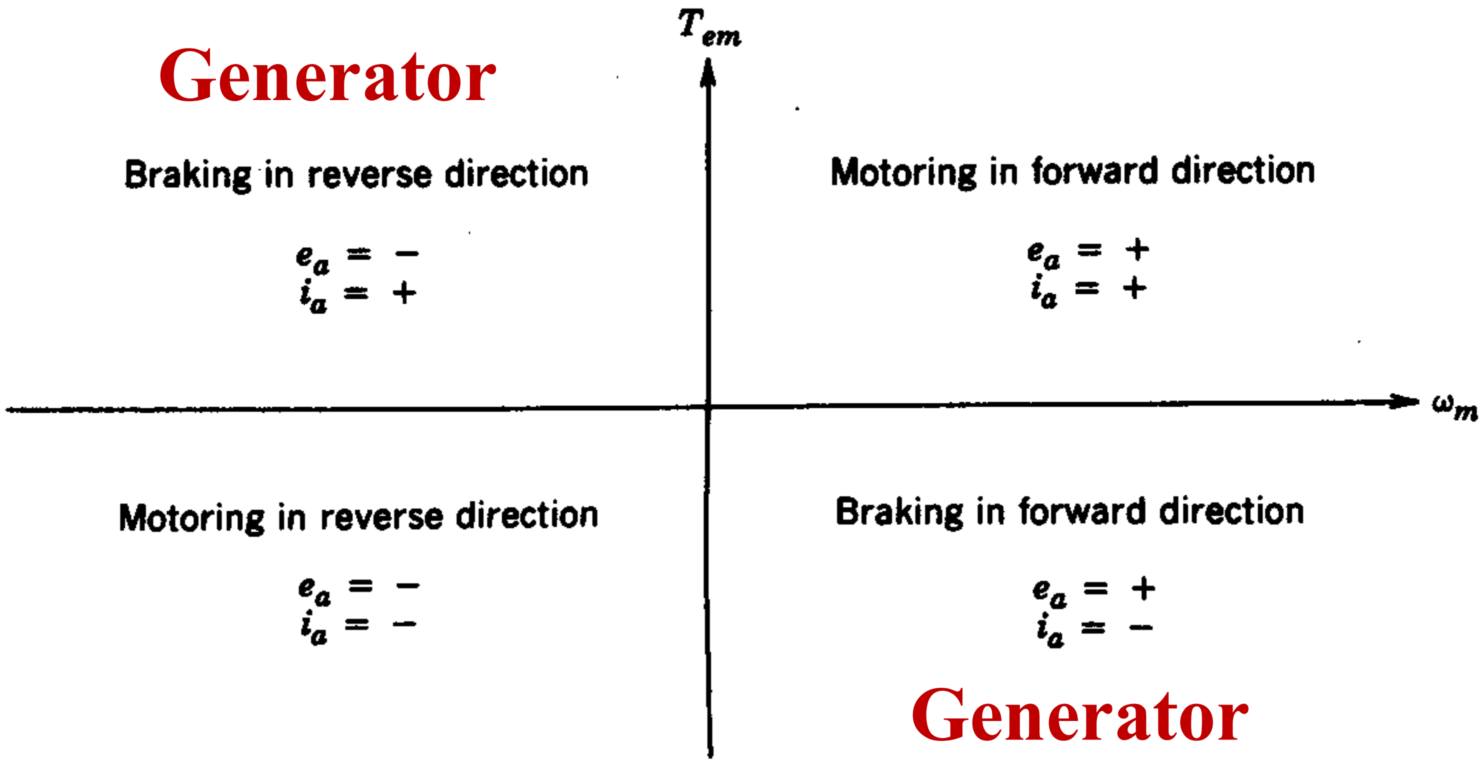


Figure 13-3 Four-quadrant operation of a dc motor.

- High performance drives may operate in all four quadrants

Permanent-magnet DC Motors

- Permanent magnets on the stator produce a constant field flux ϕ_f .

- Electromagnetic torque

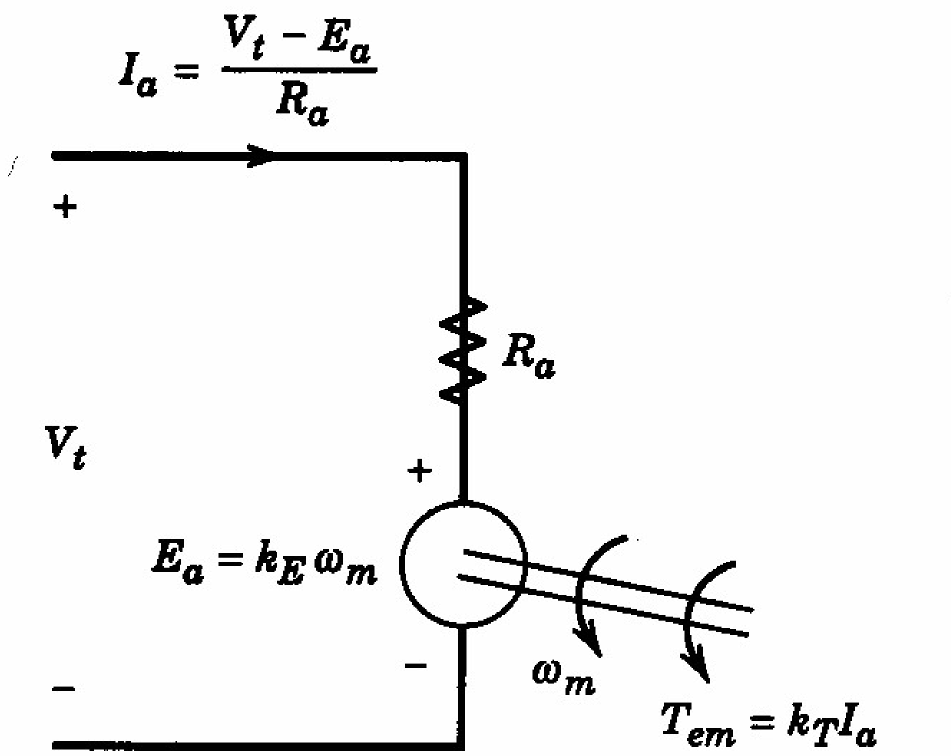
$$T_{\mathrm{em}} = k_T I_a \qquad k_T = k_t \phi_f$$

- Back-emf

$$E_{\mathrm{a}} = k_E \omega_m \qquad k_E = k_e \phi_f$$

- Voltage equation

$$V_t = E_a + R_a I_a$$



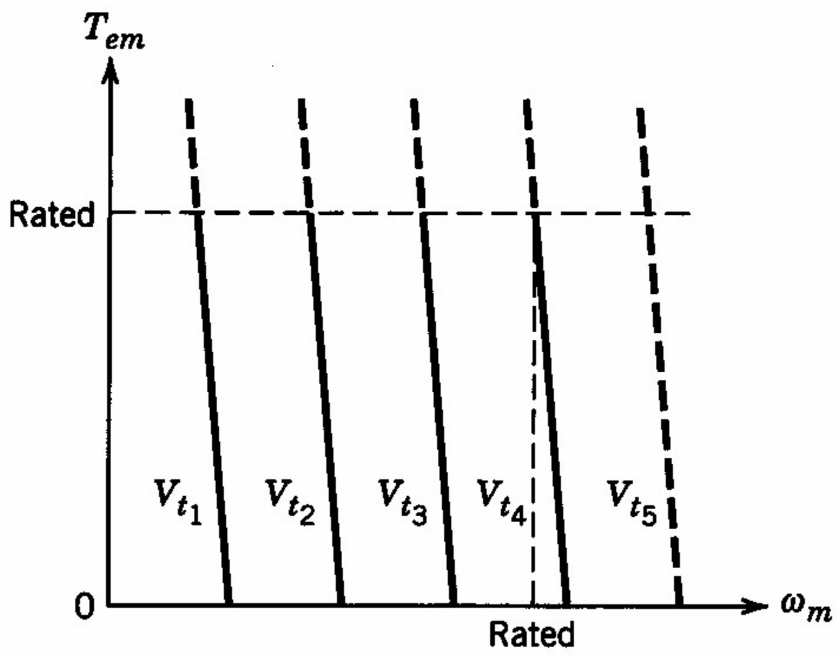
Equivalent circuit

Permanent-magnet DC Motors

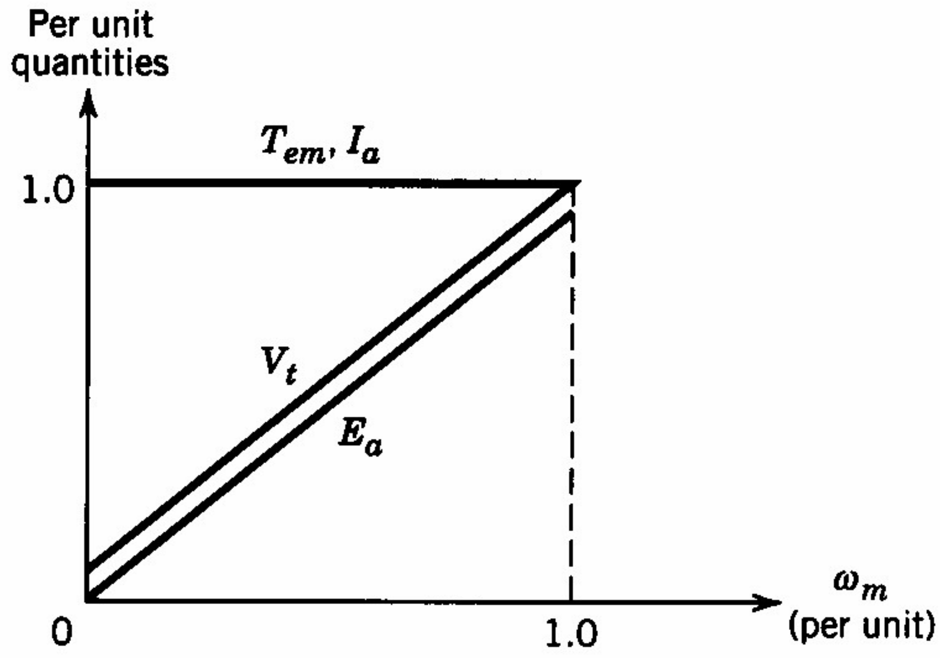
- The speed of a load with arbitrary torque can be controlled by controlling V_t in a permanent-magnet dc motor with a constant ϕ_f.

$$\omega_m = \frac{1}{k_E}\left(V_t - \frac{R_a}{k_T} T_{em}\right)$$

- ***Limitation***: the maximum speed is limited to the rated speed.



Torque-speed characteristic



Continuous torque-speed capability

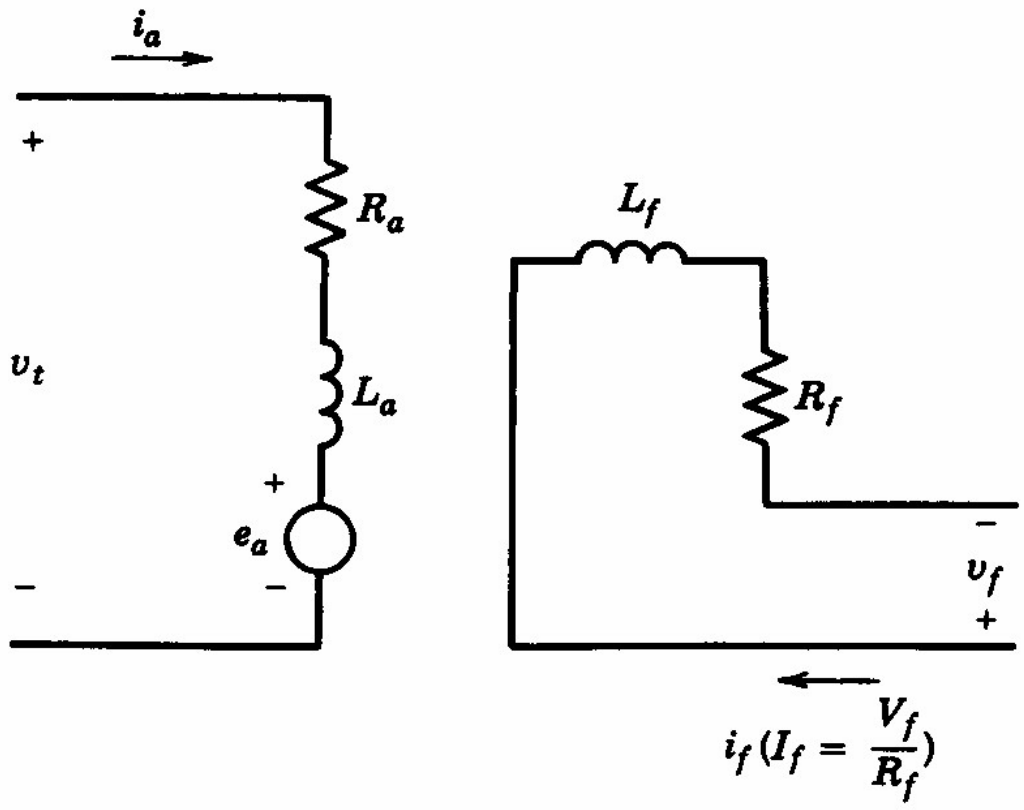
Chap.13 DC Motor Drives

DC Motors with A Separately Excited Field Winding

- The limitations of permanent-magnet DC motors can be overcome by using a separately excited field winding to adjust ϕ_f .

$$I_f = \frac{V_f}{R_f}$$

$$\omega_m = \frac{1}{k_e \phi_f}(V_t - \frac{R_a}{k_t \phi_f} T_{em})$$



Equivalent circuit

DC Motors with A Separately Excited Field Winding

Constant torque control **Constant power control**

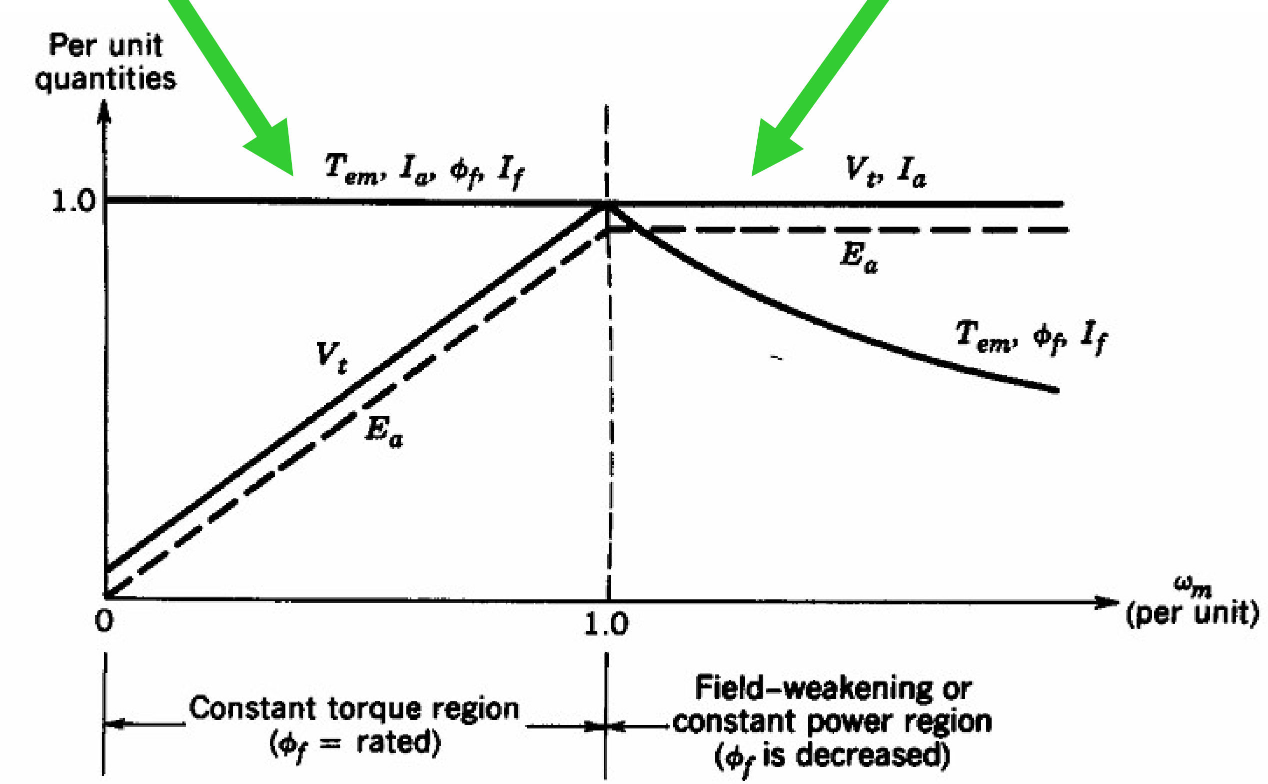


Figure 13-5 Separately excited dc motor: (*a*) equivalent circuit; (*b*) continuous torque–speed capability.

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

$$e_a = k_e \phi_f \omega_m$$

- In the field weakening region, the speed may be exceeded by 50-100% of its rated value, depending on the motor design.

DC Servo Drives

• If it were not for the disadvantages of having a commutator and brushes, the dc motor would be ideally suited for servo drives, because the instantaneous torque can be controlled linearly by controlling the armature current. $T_{em} = k_t \phi_f i_a$

13.5.1 Transfer function model

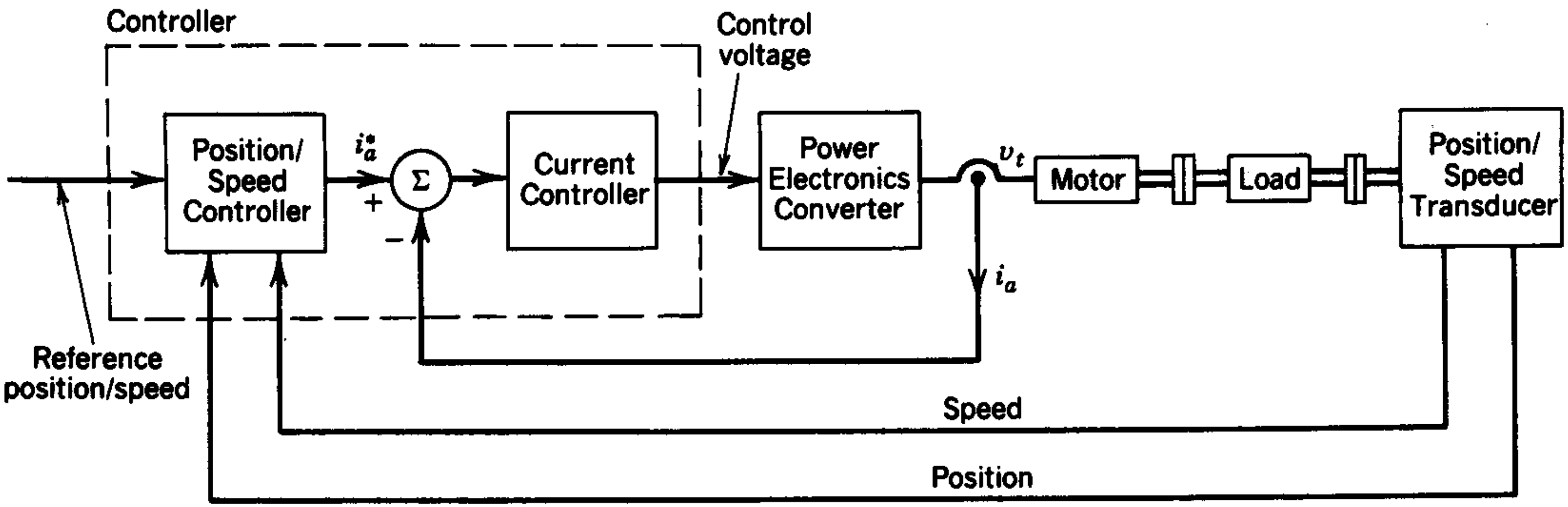


Figure 13-6 Closed-loop position/speed dc servo drive.

Three-loop control of dc servo drives

DC Servo Drives

13.5.1 Transfer function model

- Equations for analyzing small-signal dynamic performance

$$\Delta v_t = \Delta e_a + R_a \Delta i_a + L_a \frac{d}{dt}(\Delta i_a)$$

$$\Delta e_a = k_E \Delta \omega_m$$

$$\Delta T_{\text{em}} = k_T \Delta i_a$$

$$\Delta T_{\text{em}} = \Delta T_{WL} + B\Delta\omega_m + J\frac{d(\Delta\omega_m)}{dt}$$

- Take the Laplace transform

$$V_t(s) = E_a(s) + (R_a + sL_a) I_a(s)$$

$$E_a(s) = k_E \omega_m(s)$$

$$T_{\text{em}}(s) = k_T I_a(s)$$

$$T_{\text{em}}(s) = T_{WL}(s) + (B + sJ)\omega_m(s)$$

$$\omega_m(s) = s\theta_m(s)$$

DC Servo Drives

13.5.1 Transfer function model

- Take the Laplace transform

$$V_t(s) = E_a(s) + (R_a + sL_a)I_a(s)$$

$$E_a(s) = k_E\omega_m(s)$$

$$T_{em}(s) = k_T I_a(s)$$

$$T_{em}(s) = T_{WL}(s) + (B + sJ)\omega_m(s)$$

$$\omega_m(s) = s\theta_m(s)$$

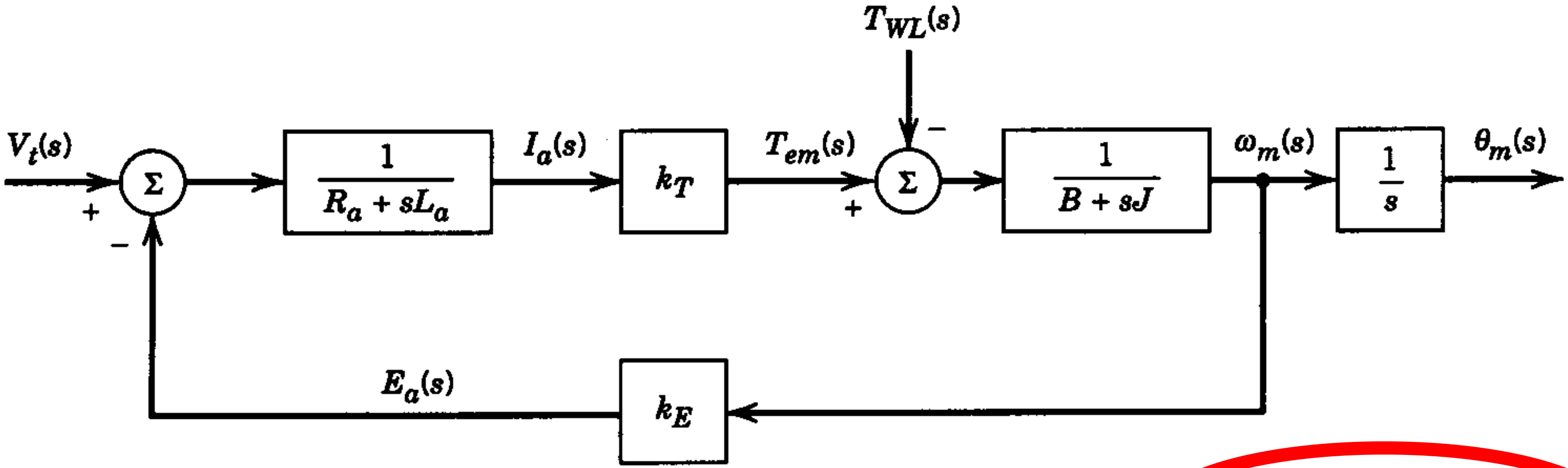


Figure 13-7 Block diagram representation of the motor and load (without any feedback).

DC Servo Drives

13.5.1 Transfer function model

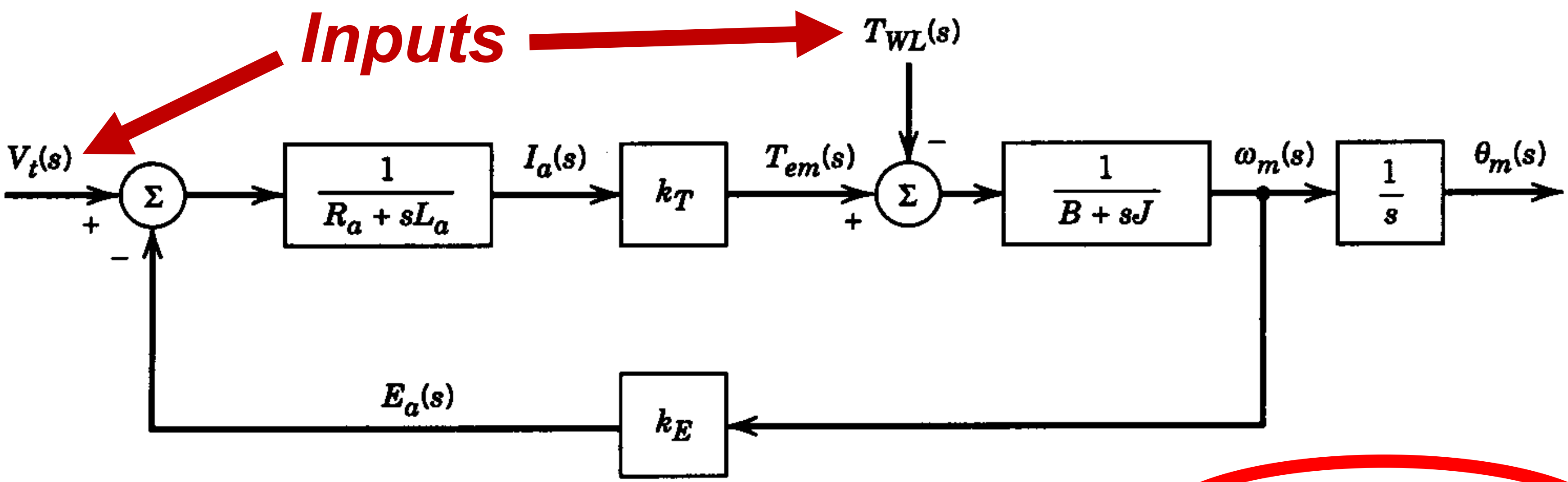


Figure 13-7 Block diagram representation of the motor and load (without any feedback).

- The superposition principle yields,

$$\omega_m(s) = \frac{k_T}{(R_a + sL_a)(sJ + B) + k_T k_E} V_t(s) - \frac{R_a + sL_a}{(R_a + sL_a)(sJ + B) + k_T k_E} T_{WL}(s)$$

DC Servo Drives

13.5.1 Transfer function model

$$\omega_m(s) = \frac{k_T}{(R_a + sL_a)(sJ + B) + k_T k_E} V_t(s) - \frac{R_a + sL_a}{(R_a + sL_a)(sJ + B) + k_T k_E} T_{WL}(s)$$

- Two transfer functions

$$G_1(s) = \left.\frac{\omega_m(s)}{V_t(s)}\right|_{T_{WL}(s)=0} = \frac{k_T}{(R_a + sL_a)(sJ + B) + k_T k_E}$$

$$G_2(s) = \left.\frac{\omega_m(s)}{T_{WL}(s)}\right|_{V_t(s)=0} = \frac{R_a + sL_a}{(R_a + sL_a)(sJ + B) + k_T k_E}$$

13.5.1 Transfer function model

- Neglect the friction term by setting $B=0$ and consider the motor without load $J=J_m$,

$$G_1(s)=\frac{k_T}{sJ_m(R_a+sL_a)+k_Tk_E}=\frac{1}{k_E(s^2\frac{L_aJ_m}{k_Tk_E}+s\frac{R_aJ_m}{k_Tk_E}+1)}$$

- Define the following constant,

Mechanical time constant $\tau_m=\dfrac{R_aJ_m}{k_Tk_E}$ **Electrical time constant** $\tau_e=\dfrac{L_a}{R_a}$

- Using time constants yields,

$$G_1(s)=\frac{\omega_m(s)}{V_t(s)}=\frac{1}{k_E(s^2\tau_m\tau_e+s\tau_m+1)}$$

13.5.1 Transfer function model

- In general, $\tau_m \gg \tau_e$ .To replace $s\tau_m$ by $s(\tau_m + \tau_e)$,

$$G_1(s) = \frac{\omega_m(s)}{V_t(s)} = \frac{1}{k_E(s^2\tau_m\tau_e + s\tau_m + 1)} \approx \frac{1}{k_E(s\tau_m + 1)(s\tau_e + 1)}$$

$$\omega_m(s) \approx \frac{1}{k_E}\frac{1}{(s\tau_m + 1)}\boxed{\frac{1}{(s\tau_e + 1)}V_t(s)}$$

DC Servo Drives

13.5.1 Transfer function model

- In general, $\tau_m \gg \tau_e$. To replace $s\tau_m$ by $s(\tau_m + \tau_e)$,

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$$\omega_m(s) \approx \frac{1}{k_E}\boxed{\frac{1}{(s\tau_m + 1)}\frac{1}{(s\tau_e + 1)}V_t(s)}$$

DC Servo Drives

13.5.1 Transfer function model

- The electrical time constant τ_e determines how quickly the armature current builds up in response to a step change ΔV_t in the terminal voltage, where the rotor speed is assumed to be constant.

$$\frac{1}{(s\tau_e + 1)} V_t(s)$$

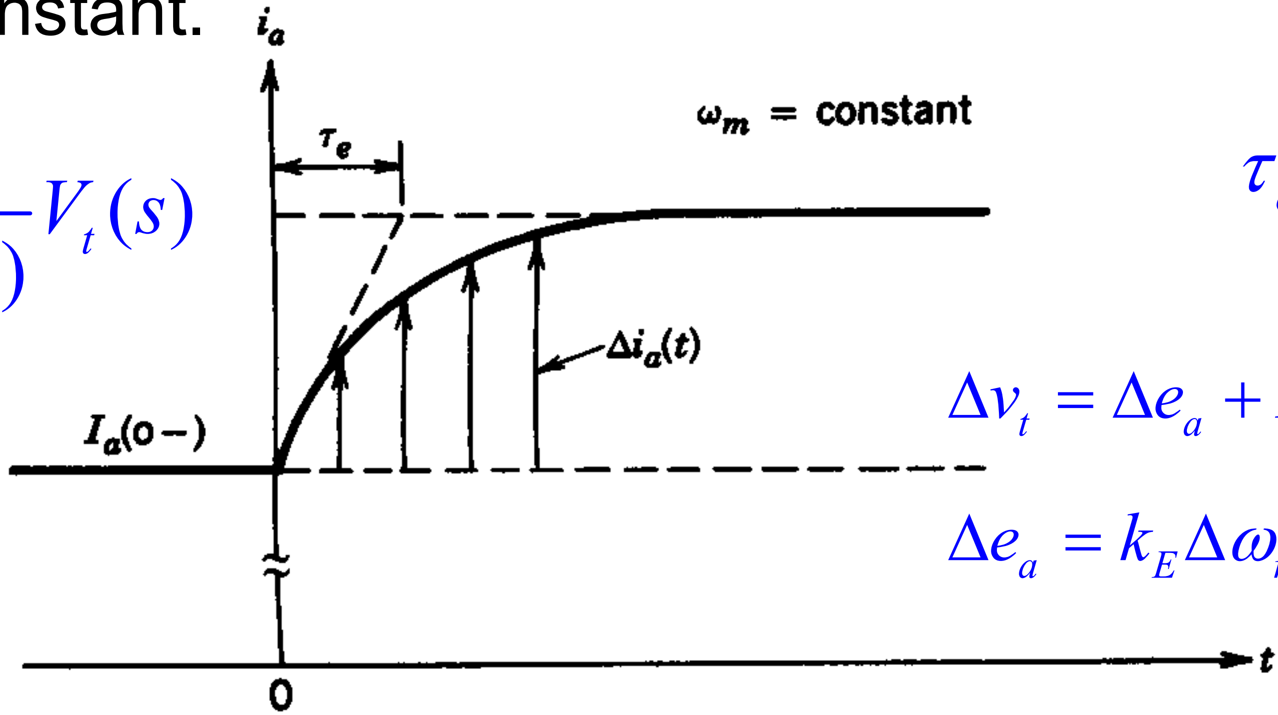


Figure 13-8 Electrical time constant τ_e; speed ω_m is assumed to be constant.

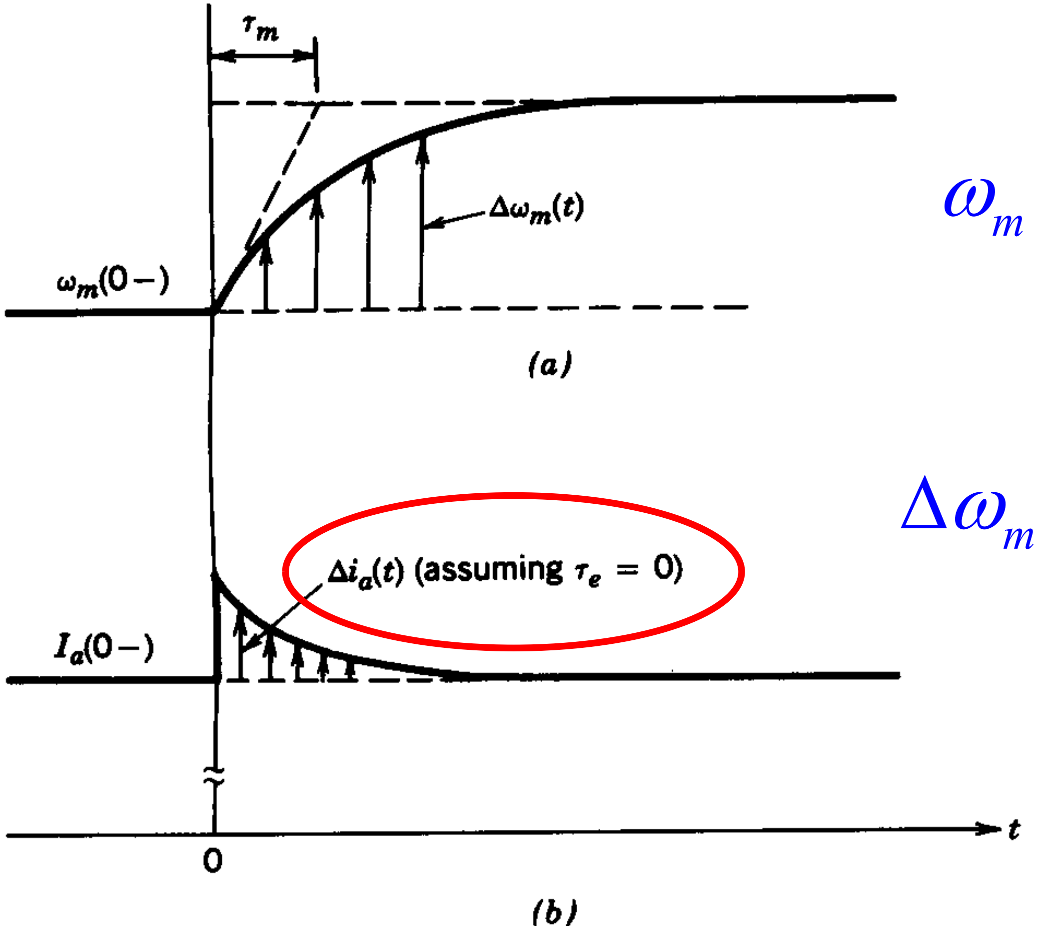
$$\tau_e = \frac{L_a}{R_a}$$

$$\Delta v_t = \Delta e_a + R_a \Delta i_a + L_a \frac{d}{dt}(\Delta i_a)$$

$$\Delta e_a = k_E \Delta \omega_m$$

DC Servo Drives

• The mechanical time constant τ_m determines how quickly the speed builds up in response to a step change ΔV_t in the terminal voltage, provided that the electrical time constant τ_e is assumed to be negligible and the armature current can change instantaneously.



$$\omega_m(s) \approx \frac{V_t(s)}{k_E(s\tau_m + 1)}$$

$$\Delta\omega_m(t) \approx \frac{\Delta v_t}{k_E}(1 - e^{-t/\tau_m})$$

Figure 13-9
Mechanical time constant τ_m; load torque is assumed to be constant.

DC Servo Drives

13.5.2 Power electronic converter

A power electronic converter supplying a dc motor should have the following capabilities:

- The converter should allow both its output voltage and current to reverse in order to realize four-quadrant operation.
- The converter should be able to operate in a current-controlled mode by holding the current at its maximum acceptable value during fast acceleration and deceleration.
- For accurate control of position, the average voltage output of the converter should vary linearly with its control input, independent of the load on the motor.
- The converter output should respond as quickly as possible to its control input.

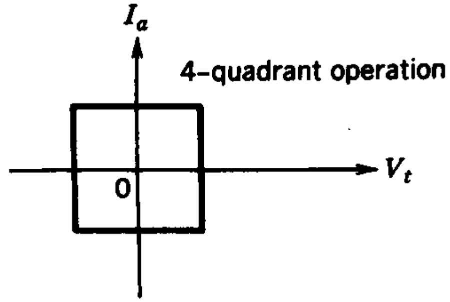
Chap.13 DC Motor Drives

DC Servo Drives

13.5.2 Power electronic converter

- A full-bridge switch-mode dc-dc converter produces a four-quadrant controllable dc output for dc motor drives.

$$V_t = k_c V_{control}$$



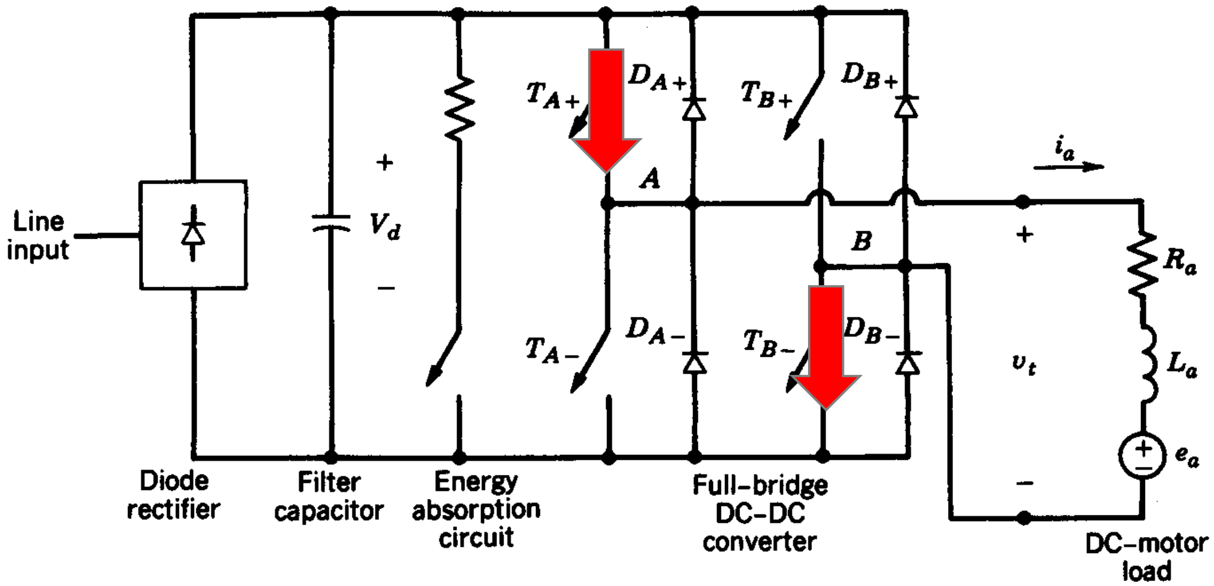


Figure 13-10 A dc motor servo drive; four-quadrant operation.

DC Servo Drives

13.5.2 Power electronic converter

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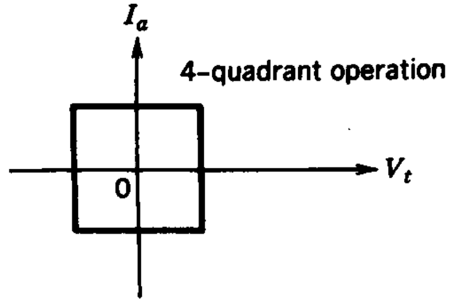

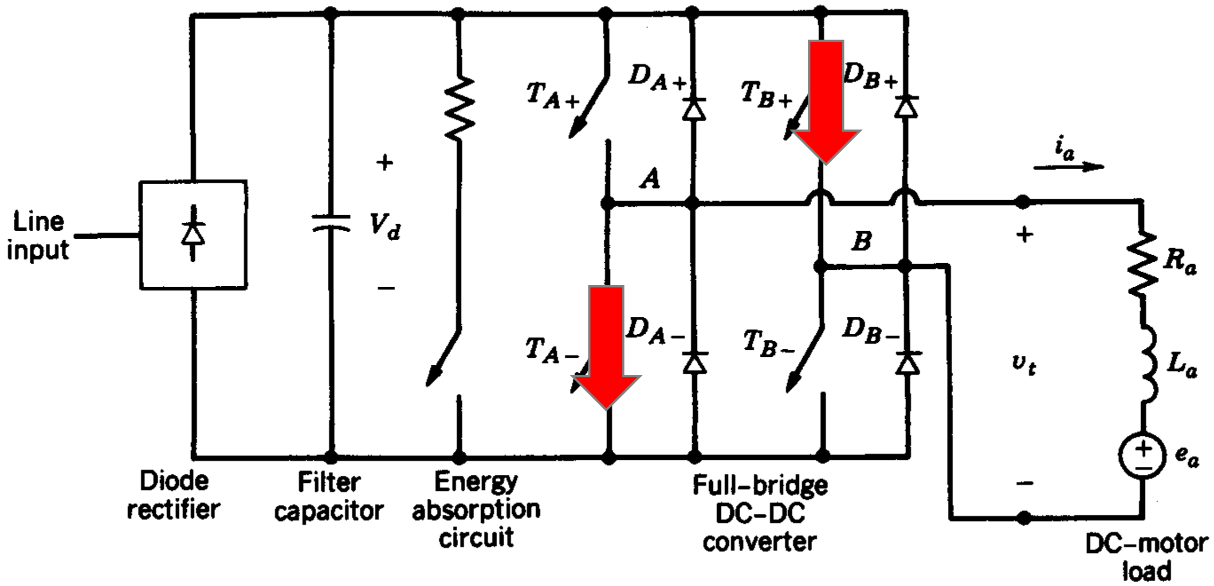

Figure 13-10 A dc motor servo drive; four-quadrant operation.

DC Servo Drives

13.5.2 Power electronic converter

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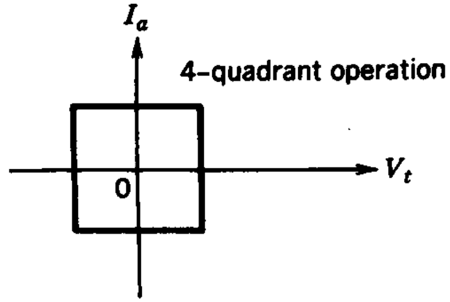


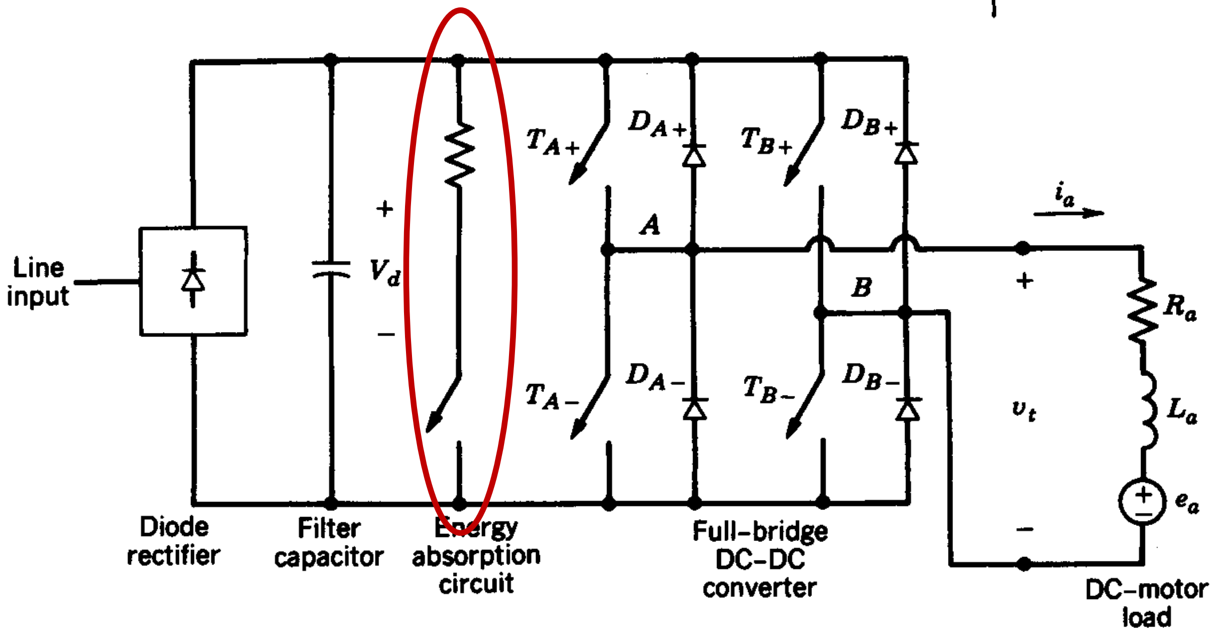


Figure 13-10 A dc motor servo drive; four-quadrant operation.

DC Servo Drives

13.5.3 Ripple in the armature current

- The peak-to-peak ripple in the armature current caused by the switch-mode dc-dc converter impacts on the torque pulsations and heating of the motor.

$$v_t(t) = V_t + v_r(t)$$

$$i_a(t) = I_a + i_r(t)$$

Ripple components $v_t(t), i_r(t)$

- The armature circuit equation:

$$T_{em} - T_{WL} = J\frac{d\omega_m}{dt}$$

$$V_t + v_r(t) = E_a + R_a[I_a + i_r(t)] + L_a\frac{di_r(t)}{dt}$$

$$V_t = E_a + R_a I_a \qquad v_r(t) = R_a i_r(t) + L_a\frac{di_r(t)}{dt}$$

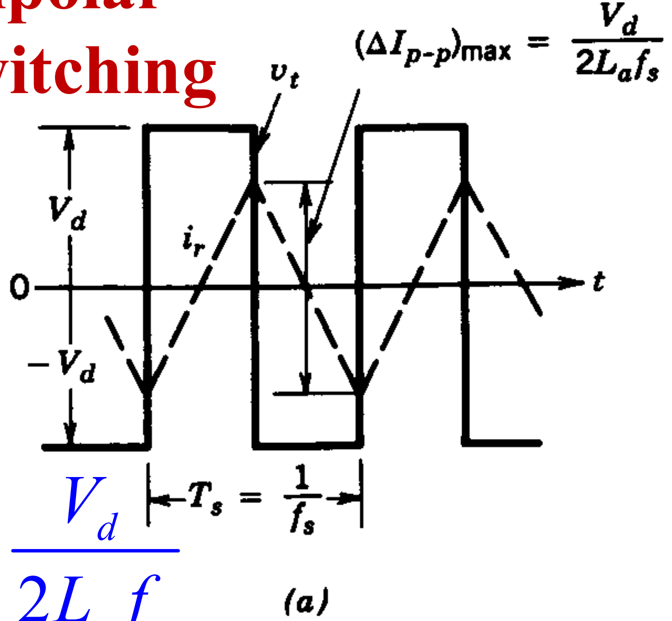
DC Servo Drives

- The ripple current is primarily determined by the armature inductance.

$$v_r(t) \approx L_a \frac{di_r(t)}{dt}$$

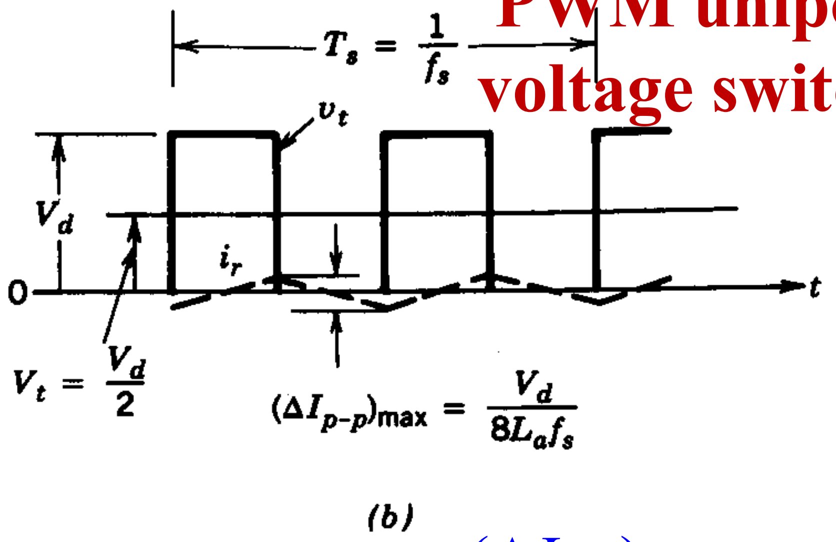
- The ripple voltage is maximum when the average output voltage is zero and all switches operate at equal duty ratios

PWM bipolar voltage switching



$$(\Delta I_{\text{p-p}})_{\text{max}} = \frac{V_d}{2L_a f_s}$$

PWM unipolar voltage switching



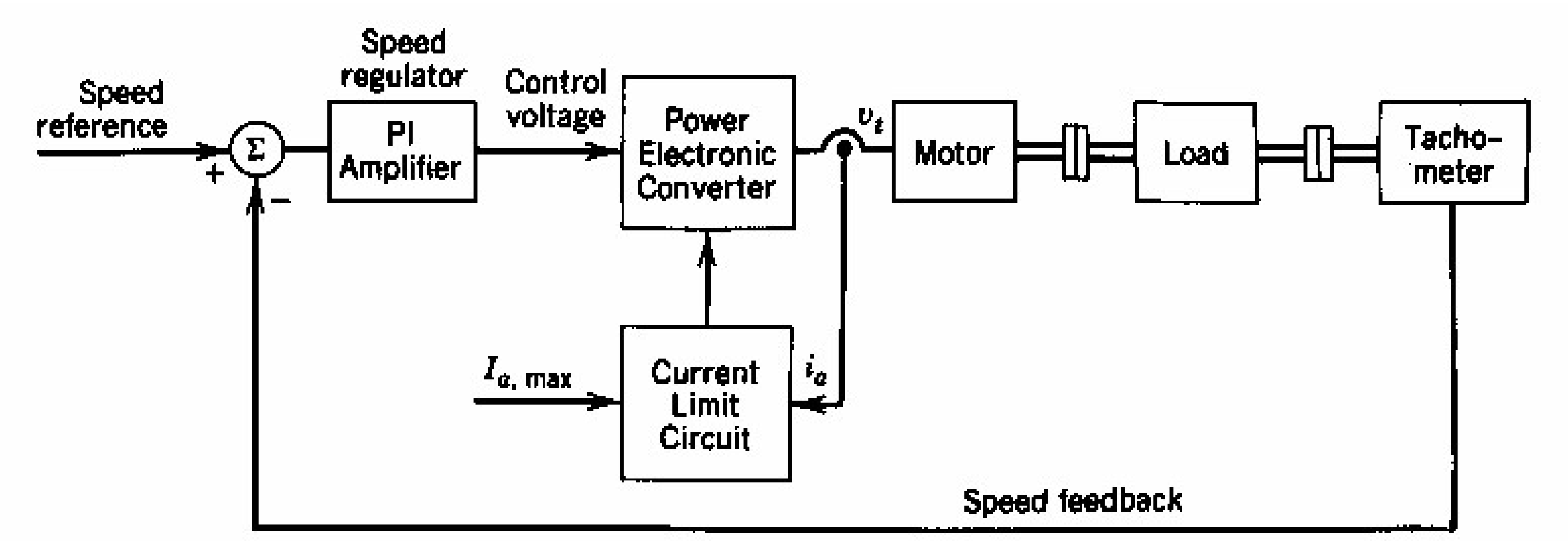
$$(\Delta I_{\text{p-p}})_{\text{max}} = \frac{V_d}{8L_a f_s}$$

Figure 13-11 Ripple i_r in the armature current: (a) PWM bipolar voltage switching, $V_t = 0$; (b) PWM unipolar voltage switching, $V_t = \frac{1}{2}V_d$.

DC Servo Drives

13.5.4 Control of servo drives

• The current-limiting circuit operates only when the drive current tries to exceed an acceptable limit $I_{a,\max}$ during fast accelerations and decelerations.

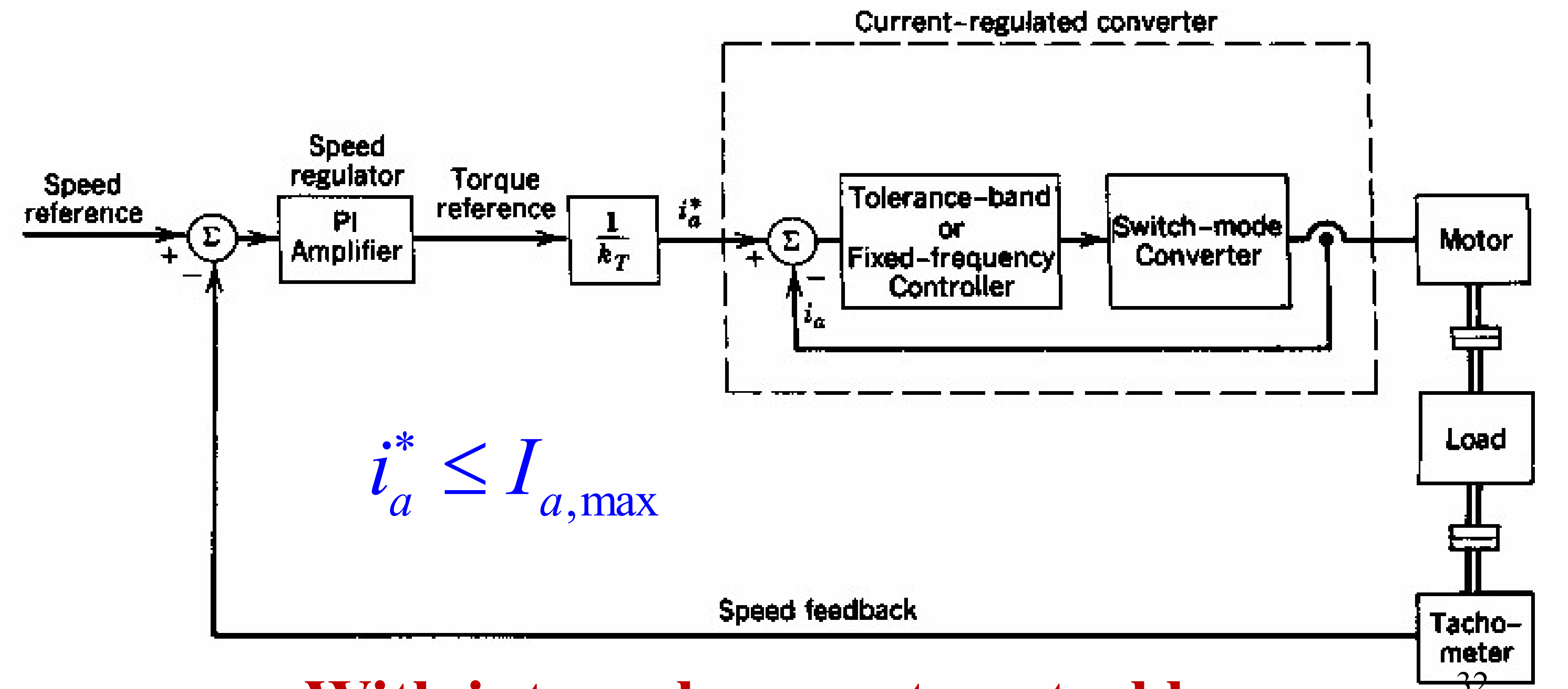


No internal current control loop

DC Servo Drives

13.5.4 Control of servo drives

- To improve the dynamic response in high-performance servo drives, an internal current loop is used to control the armature current and torque directly.



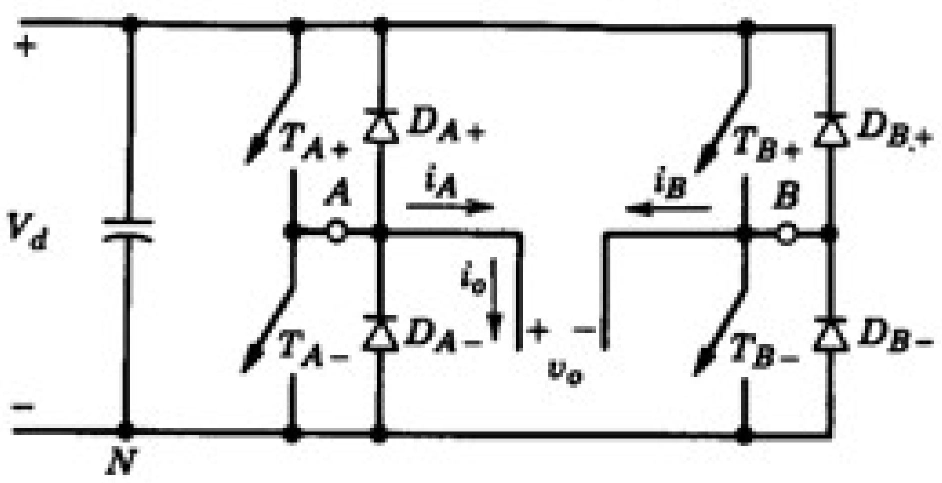
$$i_a^* \le I_{a,\max}$$

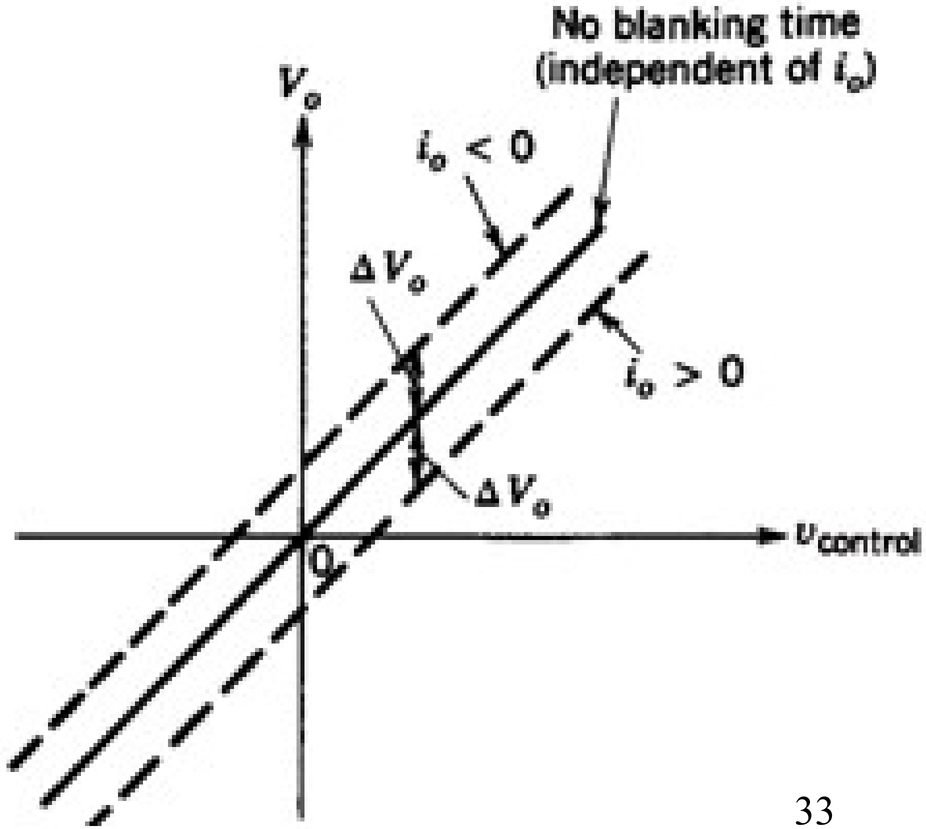
With internal current control loop

DC Servo Drives

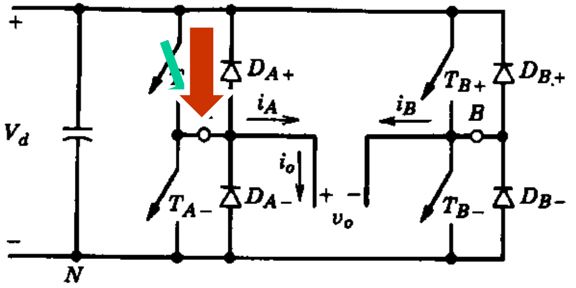
13.5.5 Nonlinearity due to blanking time

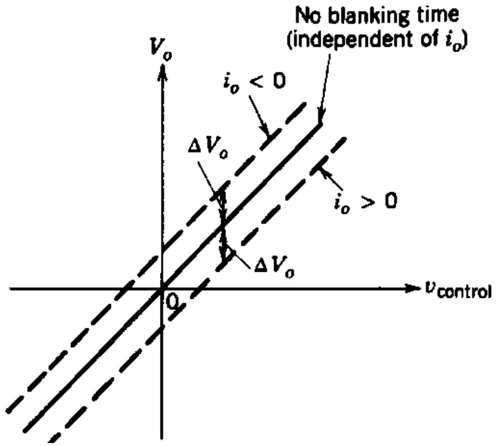
- The blanking time of PWM dc-dc converters causes output voltage errors.

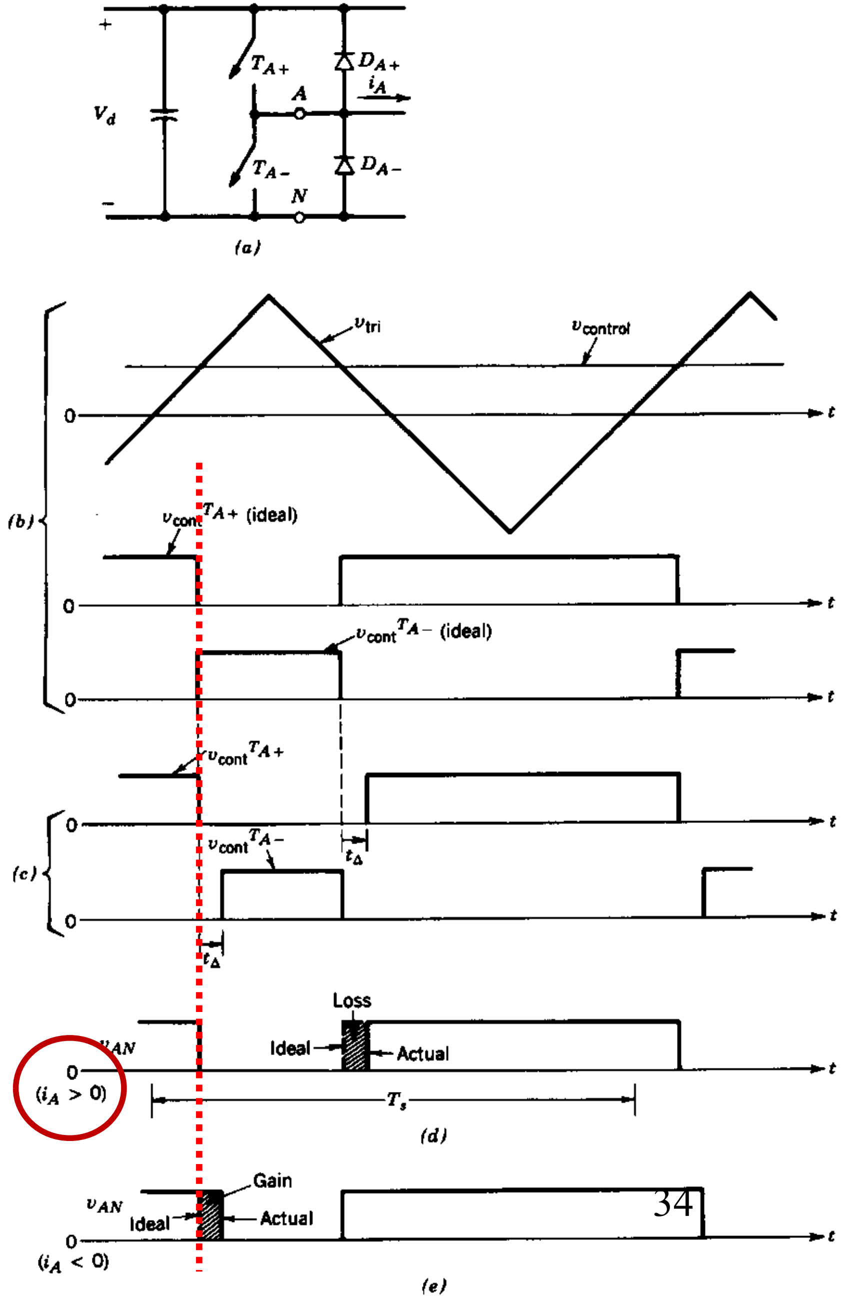




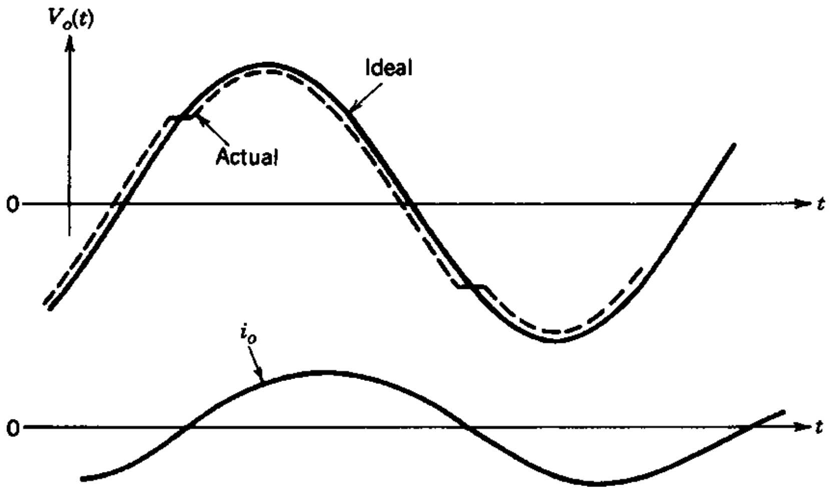
5.4 Effects of Blanking Time



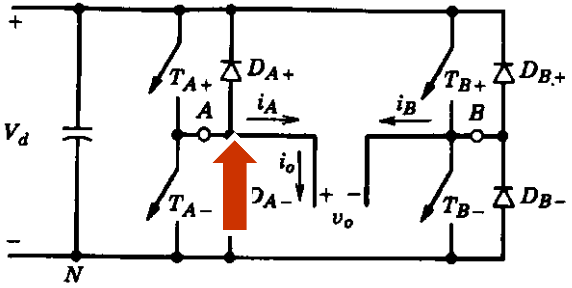


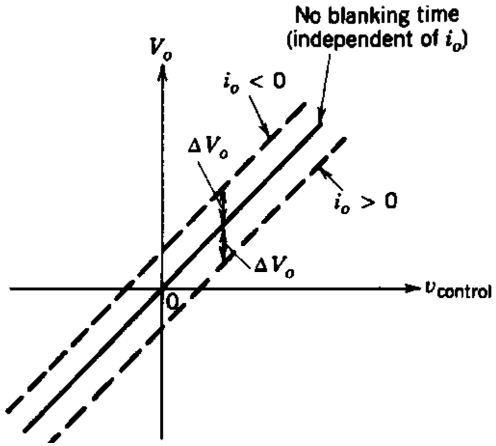


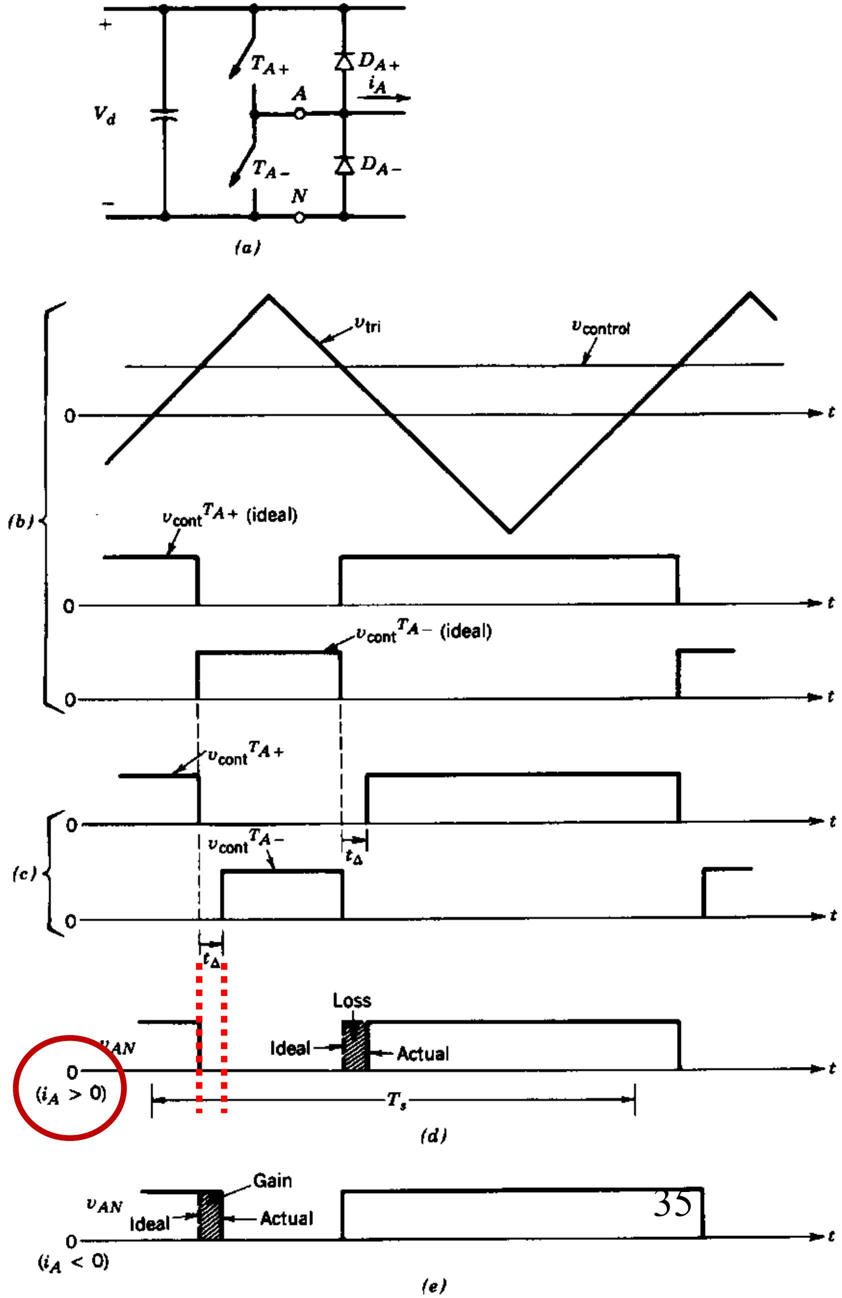
Voltage jump when the current reverses direction



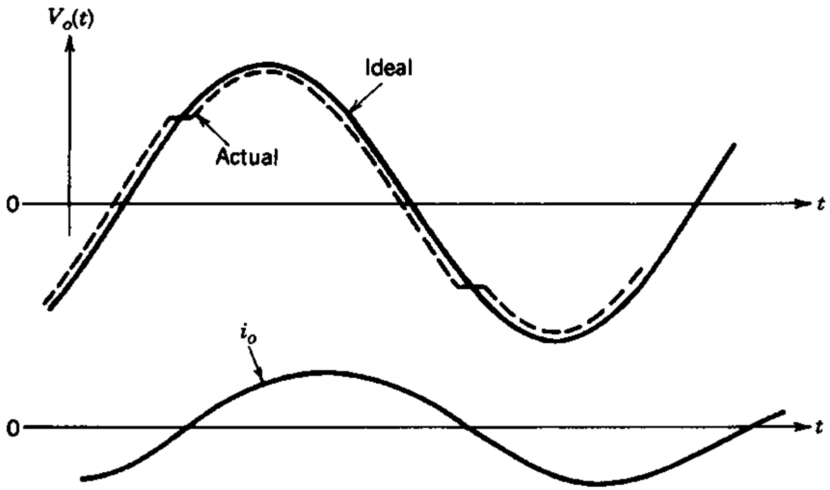
5.4 Effects of Blanking Time



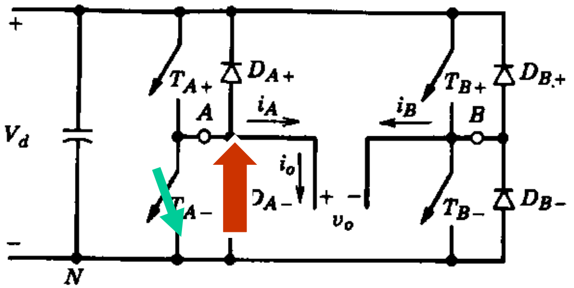


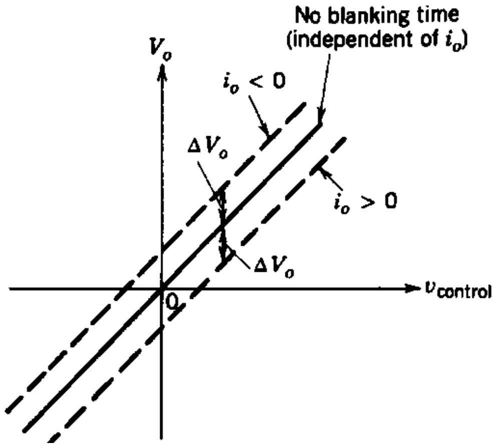


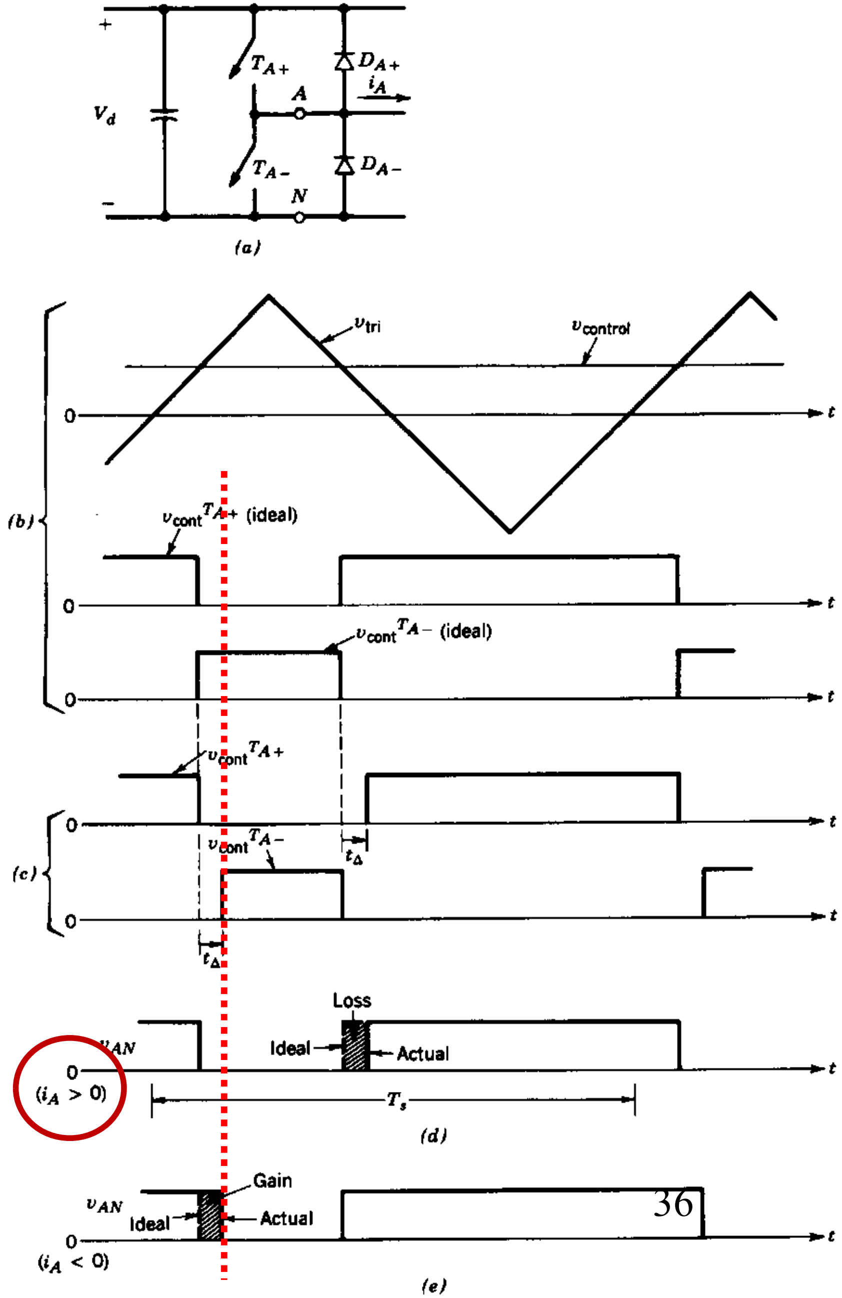
Voltage jump when the current reverses direction



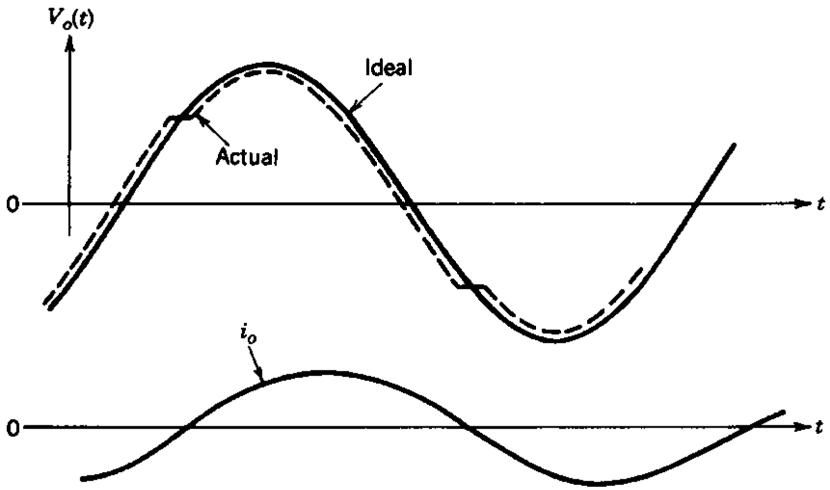
5.4 Effects of Blanking Time



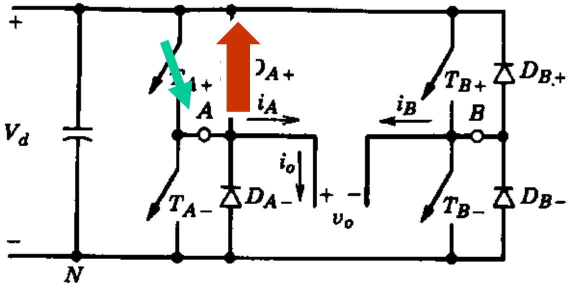


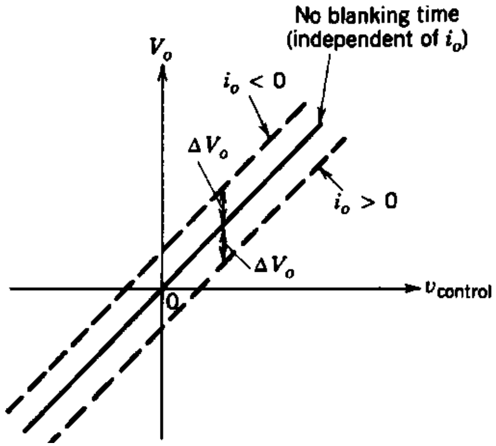


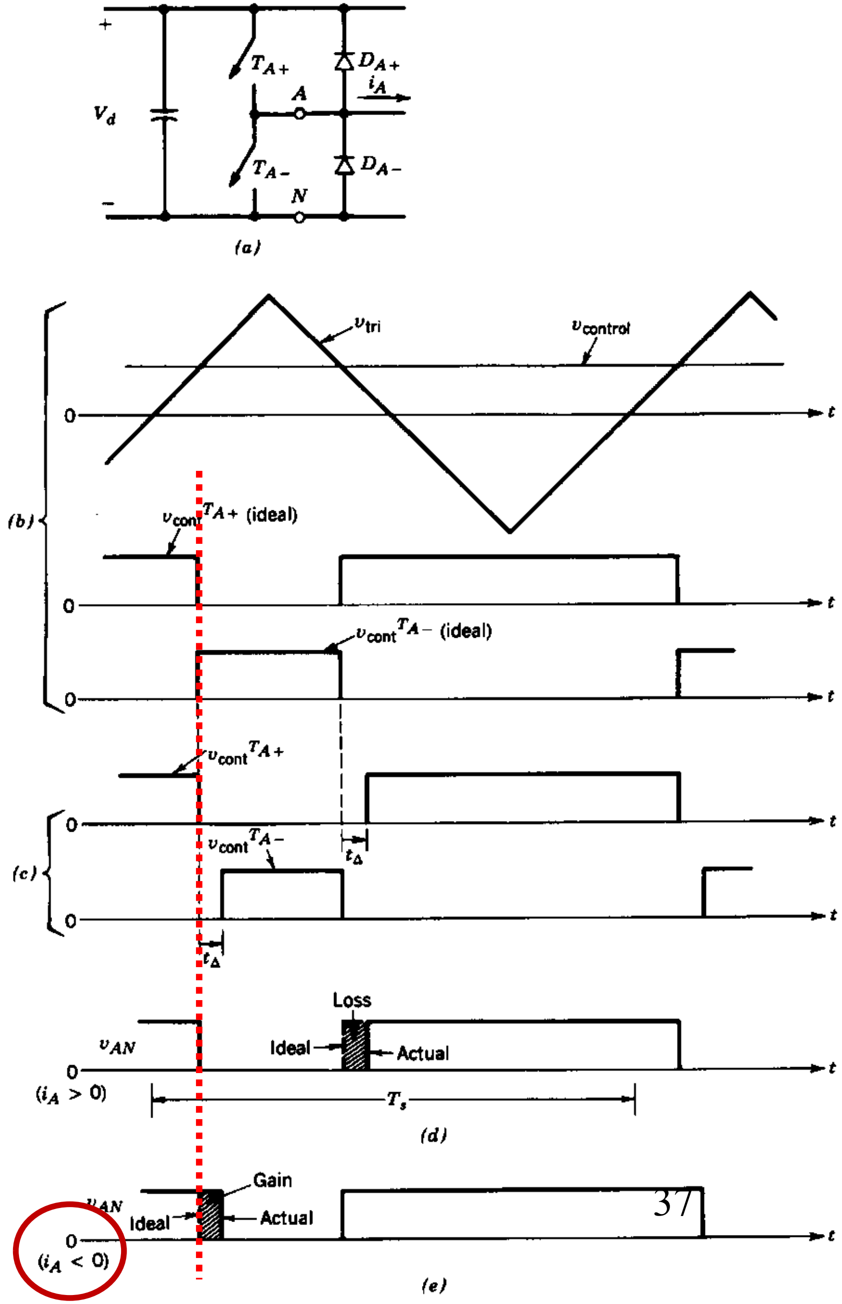
Voltage jump when the current reverses direction



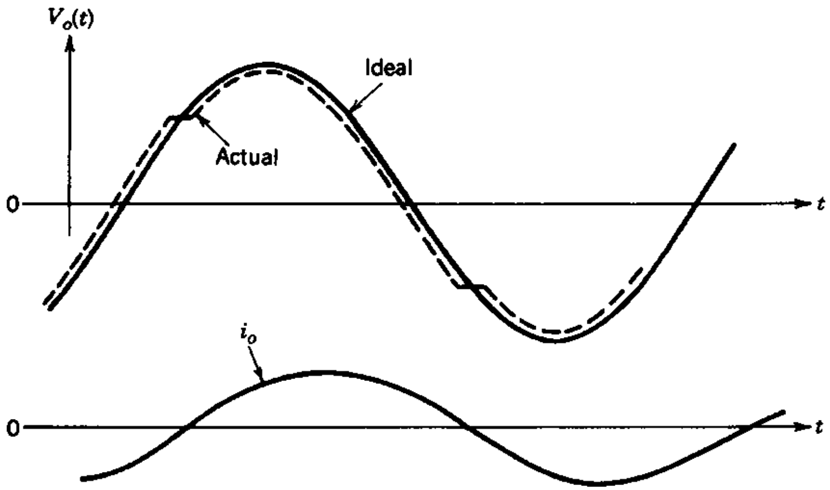
5.4 Effects of Blanking Time



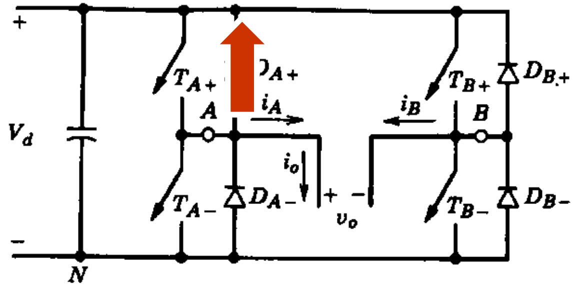


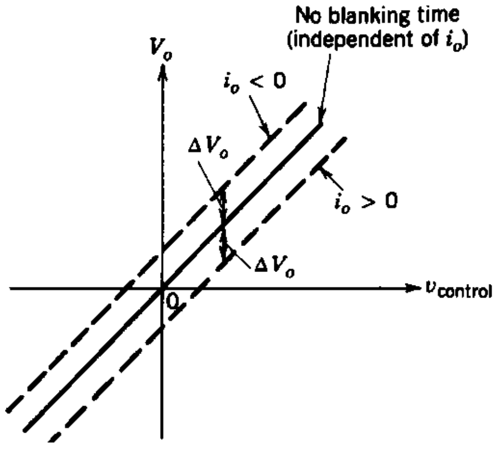


Voltage jump when the current reverses direction

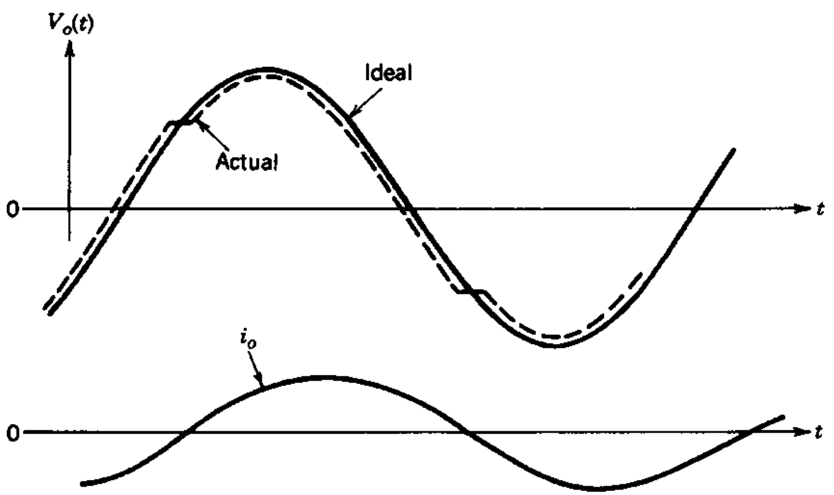


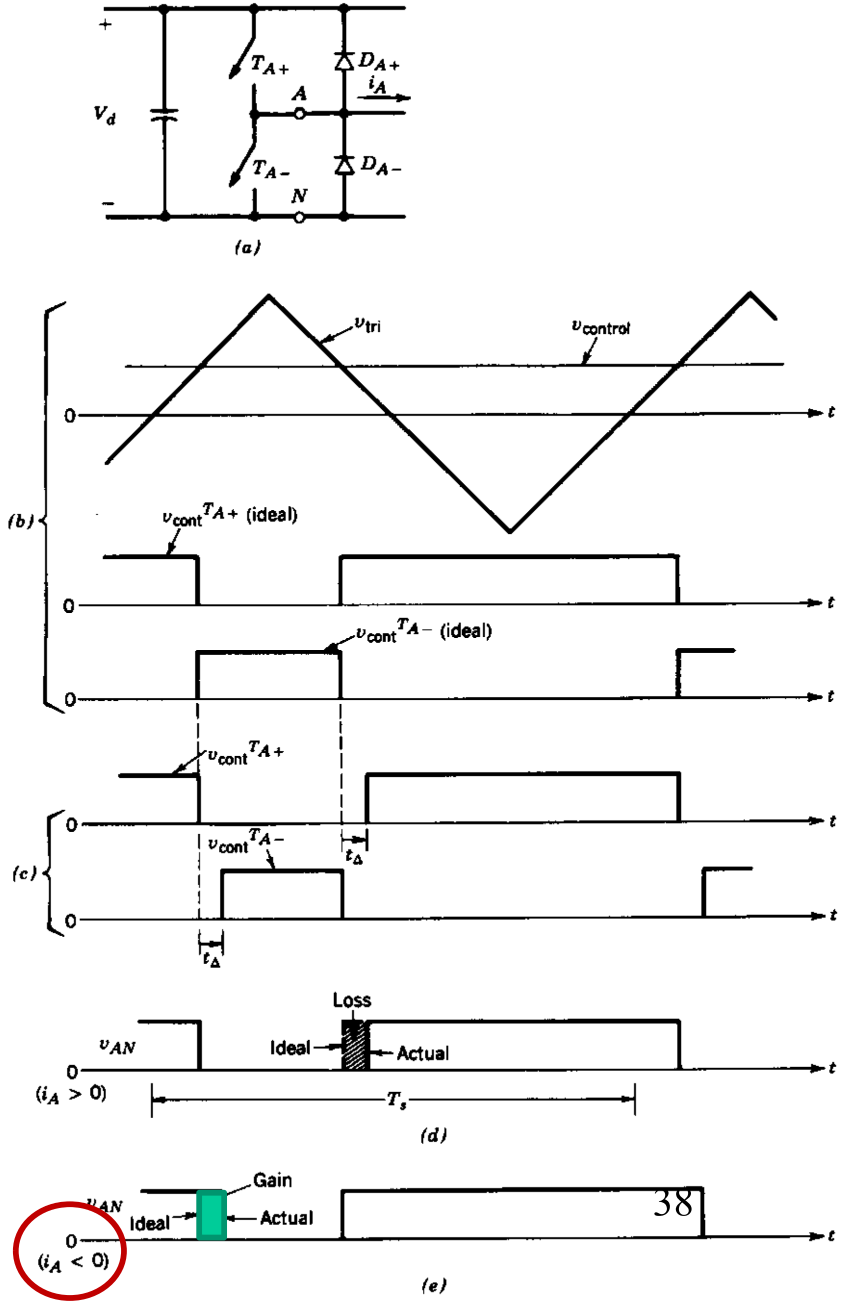
5.4 Effects of Blanking Time



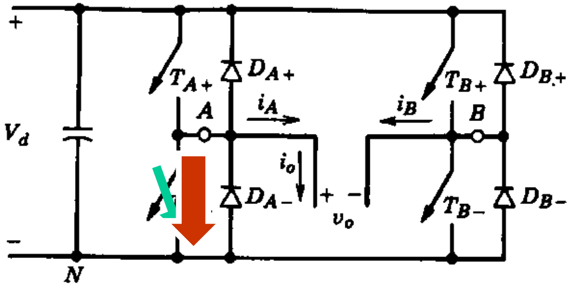


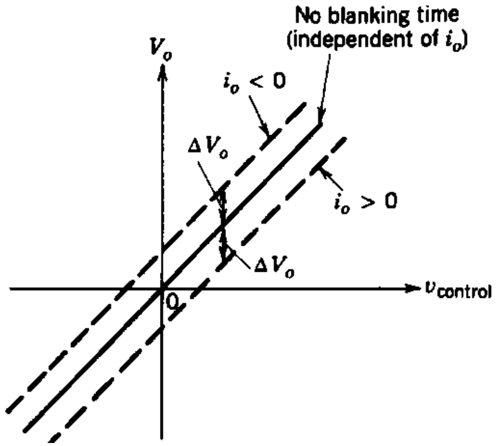
Voltage jump when the current reverses direction

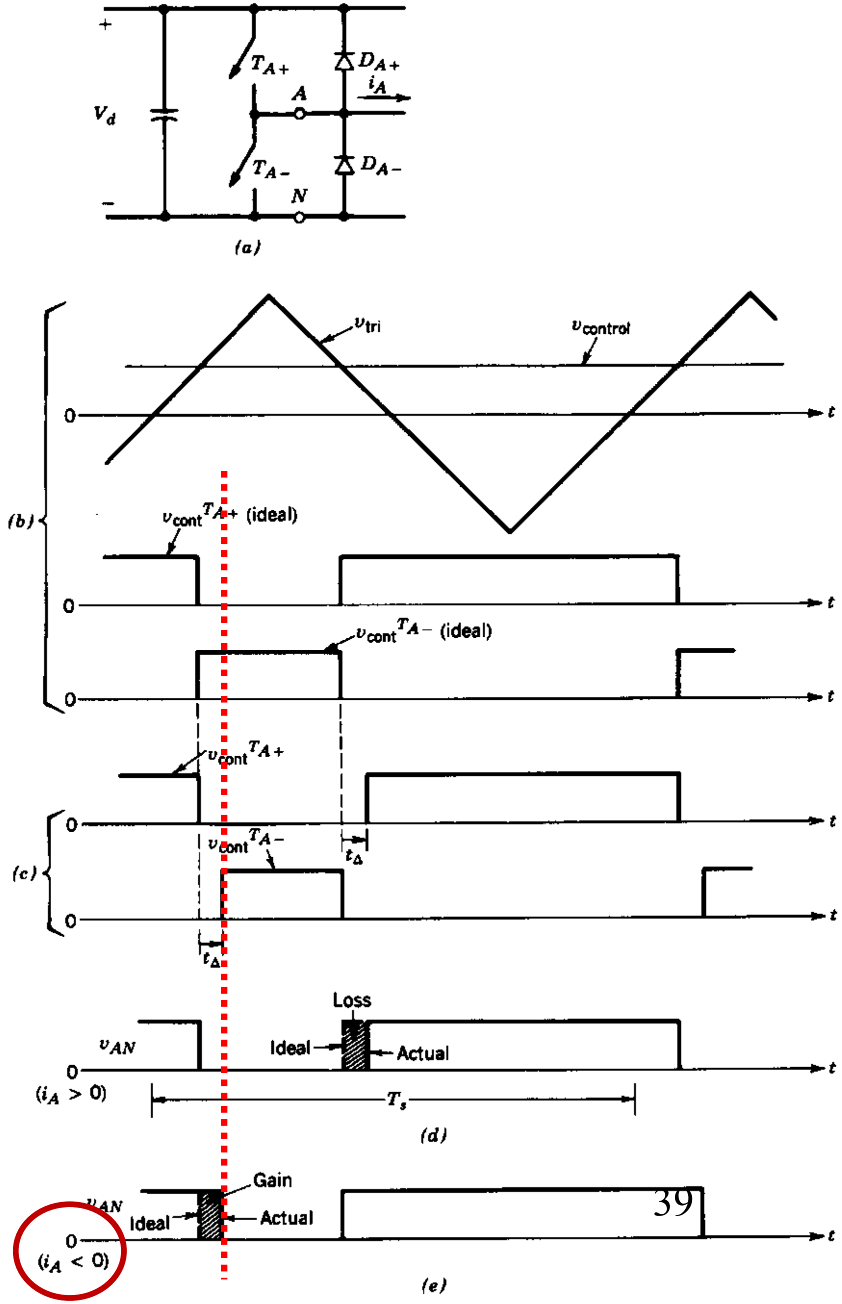




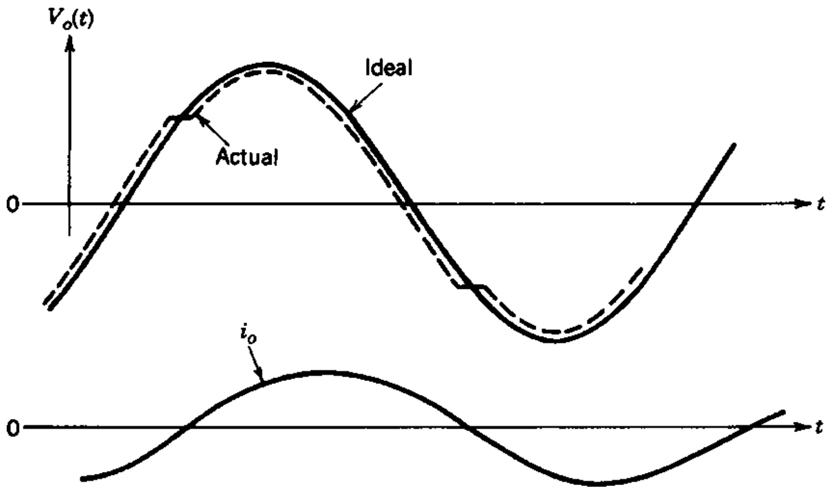
5.4 Effects of Blanking Time







Voltage jump when the current reverses direction



DC Servo Drives

13.5.5 Nonlinearity due to blanking time

• The blanking time of PWM dc-dc converters causes output voltage errors.
• The effects due to blanking time on the drive performance can be minimized by using the current-controlled mode converters.

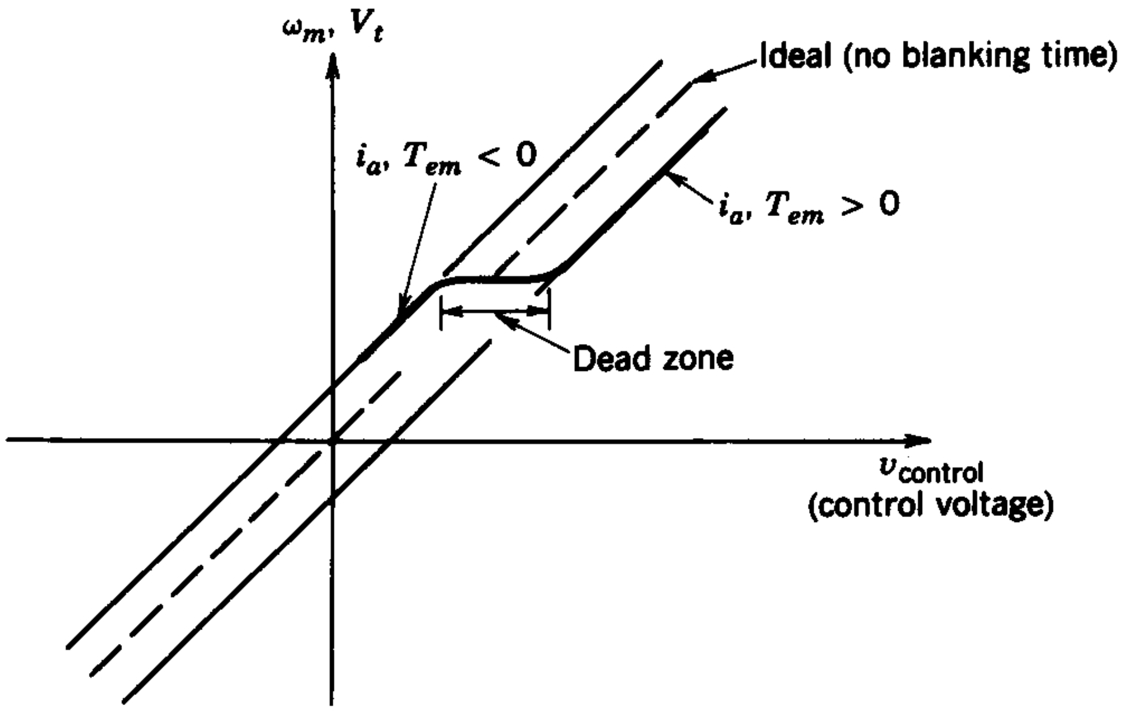
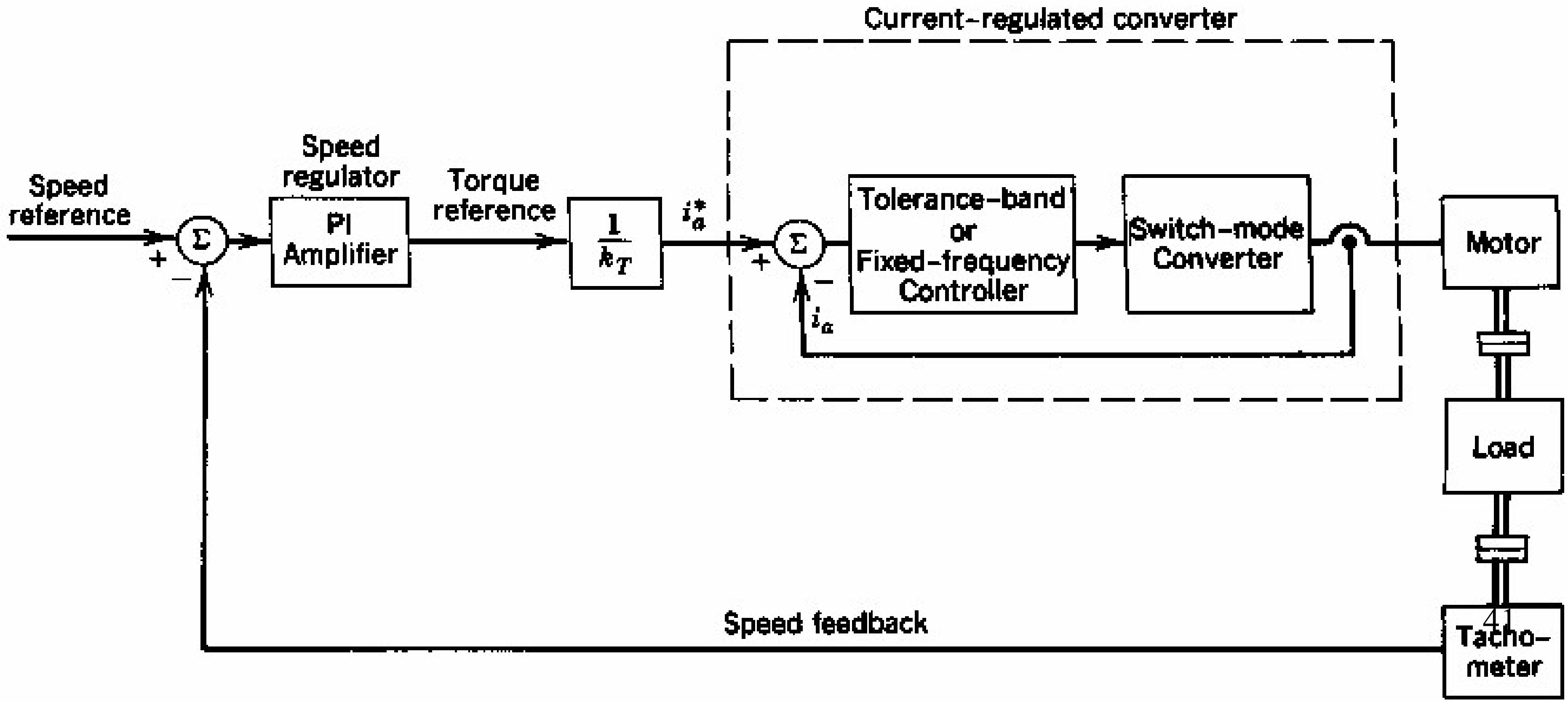


Figure 13-13 Effect of blanking time.

DC Servo Drives

13.5.5 Nonlinearity due to blanking time

- The blanking time of PWM dc-dc converters causes output voltage errors.
- The effects due to blanking time on the drive performance can be minimized by using the current-controlled mode converters.

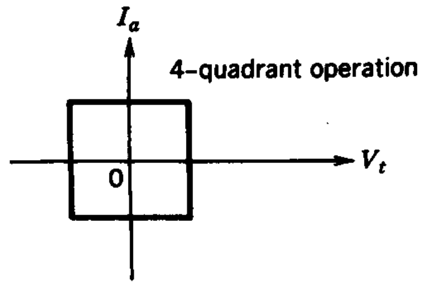


Adjustable-speed DC Drives

- Unlike servo drives, the response time to speed and torque commands is not as critical in adjustable-speed drives.

13.6.1 Switch-mode dc-dc converter

$$T_{em} = k_t \phi_f i_a \qquad e_a = k_e \phi_f \omega_m$$



- If a four-quadrant operation is needed and a switch-mode converter is utilized, then the full-bridge converter is used.

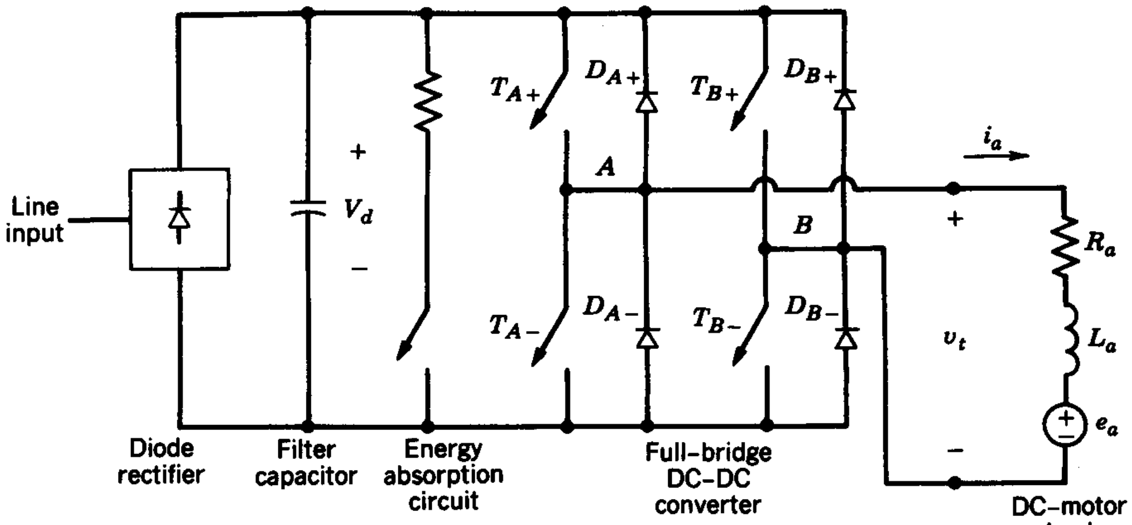


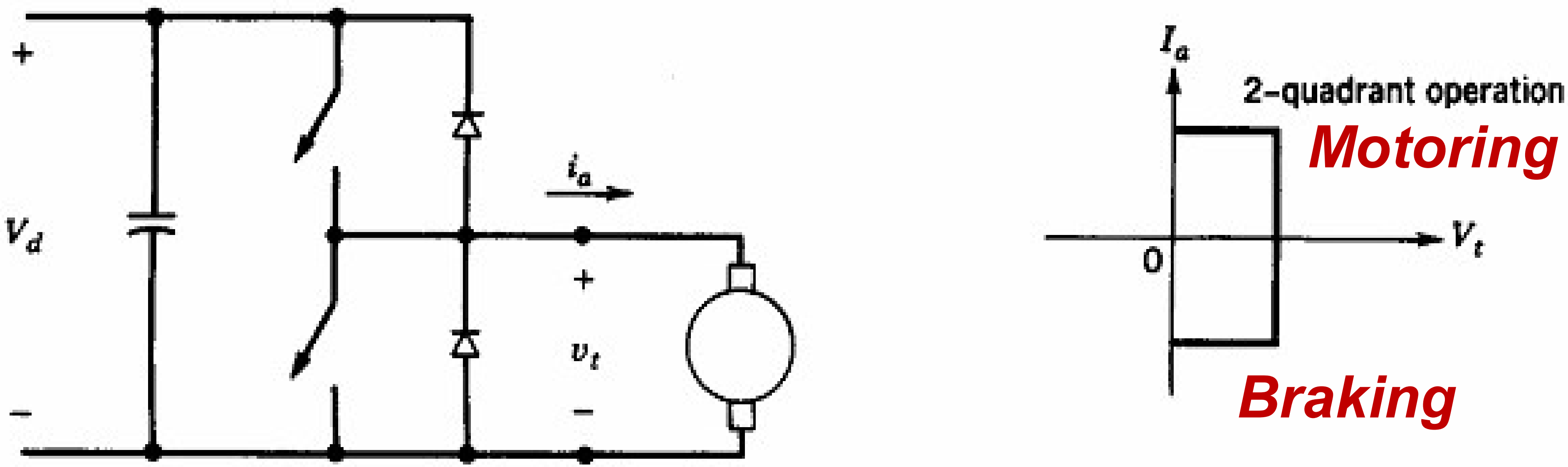
Figure 13-10 A dc motor servo drive; four-quadrant operation.

Adjustable-speed DC Drives

13.6.1 Switch-mode dc-dc converter

- If the speed does not have to reverse but braking is needed, then the two-quadrant converter can be used.

$$T_{\text{em}} = k_t \phi_f i_a \qquad e_a = k_e \phi_f \omega_m$$



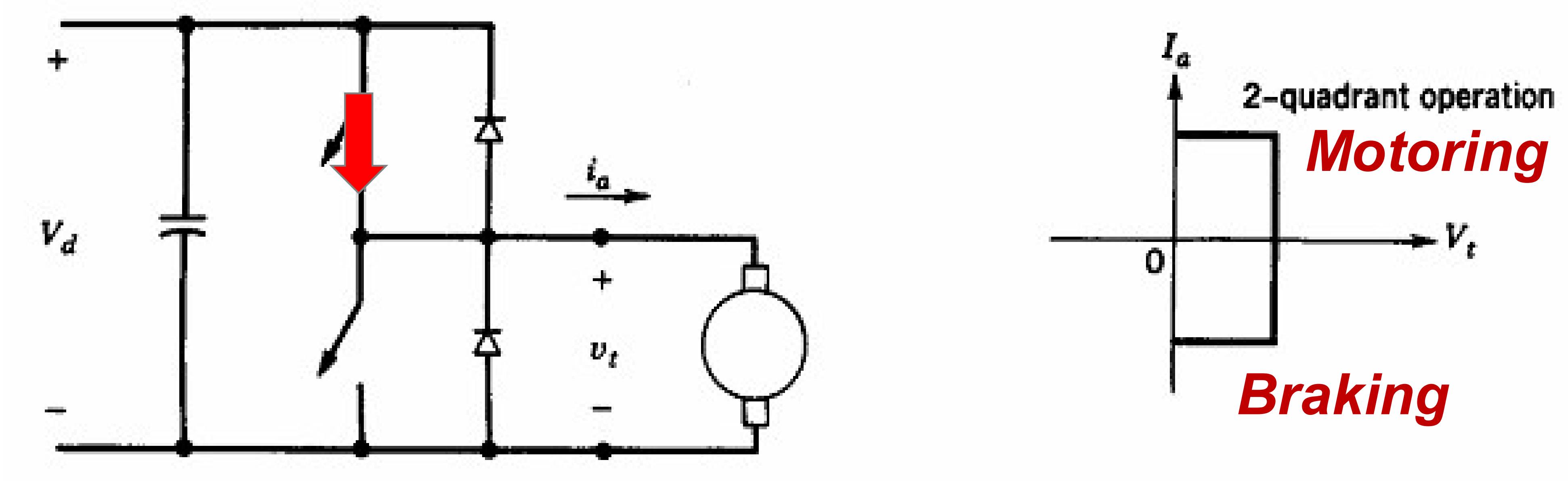
Two-quadrant operation

Adjustable-speed DC Drives

13.6.1 Switch-mode dc-dc converter

• If the speed does not have to reverse but braking is needed, then the two-quadrant converter can be used.

$$T_{\text{em}} = k_t \phi_f i_a \qquad e_a = k_e \phi_f \omega_m$$



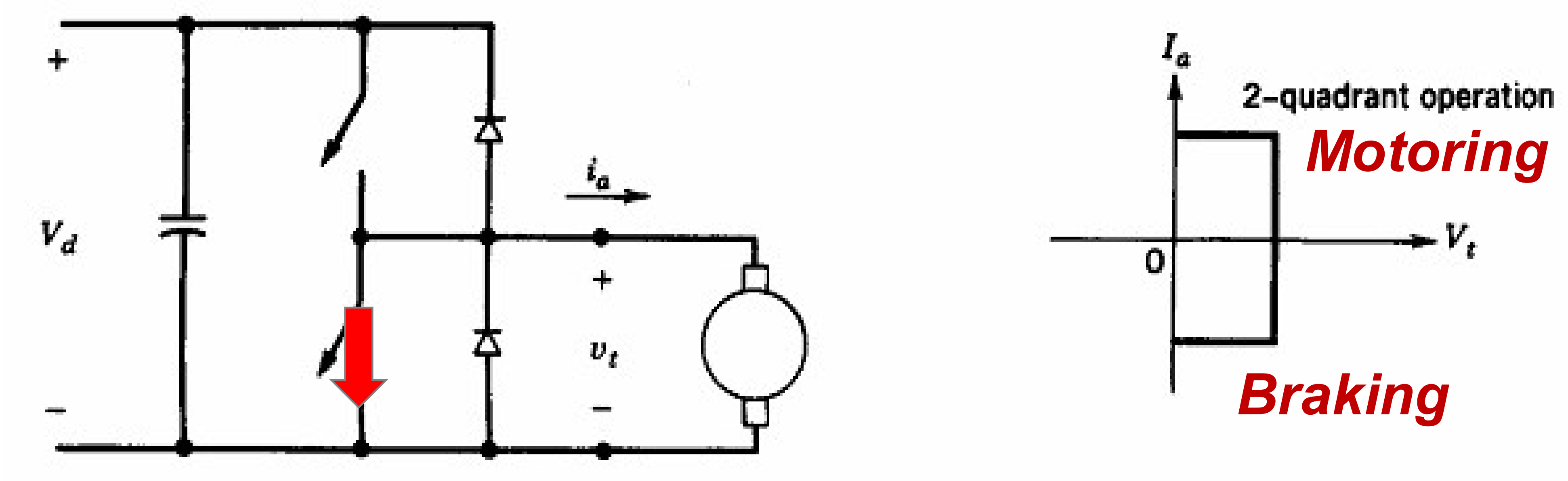
Two-quadrant operation

Adjustable-speed DC Drives

13.6.1 Switch-mode dc-dc converter

- If the speed does not have to reverse but braking is needed, then the two-quadrant converter can be used.

$$T_{\mathrm{em}} = k_t \phi_f i_a \qquad e_a = k_e \phi_f \omega_m$$

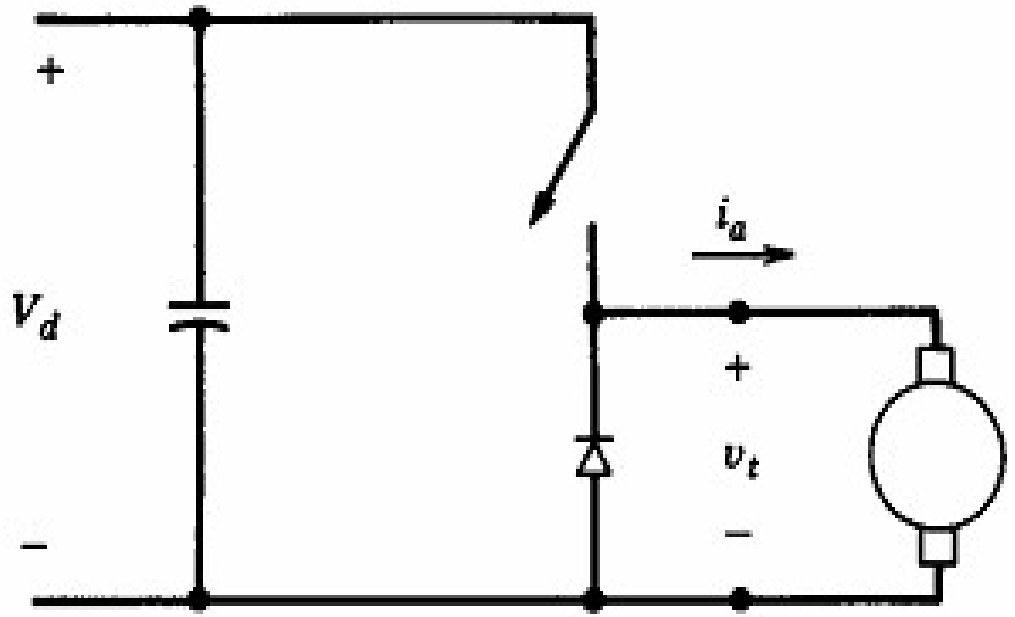


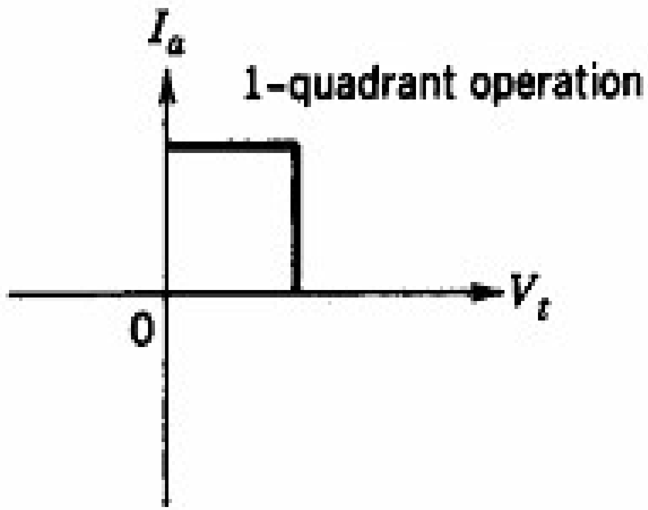
Two-quadrant operation

Adjustable-speed DC Drives

13.6.1 Switch-mode dc-dc converter

• For a single-quadrant operation where the speed remains unidirectional and braking is not required, the step-down converter can be used.





Single-quadrant operation

Adjustable-speed DC Drives

13.6.2 Line-frequency controlled converter

- In large power adjustable-speed dc drives, it may be economical to utilize a line-frequency controlled converter (phase-controlled converter).

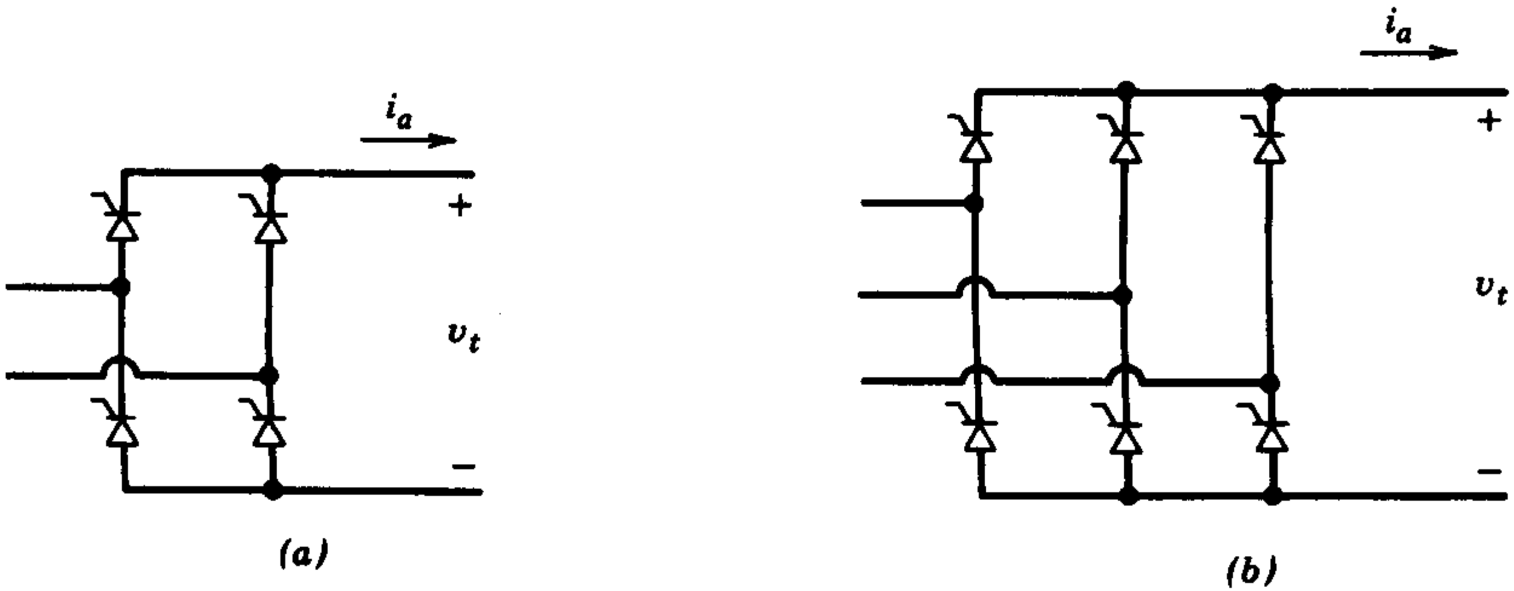
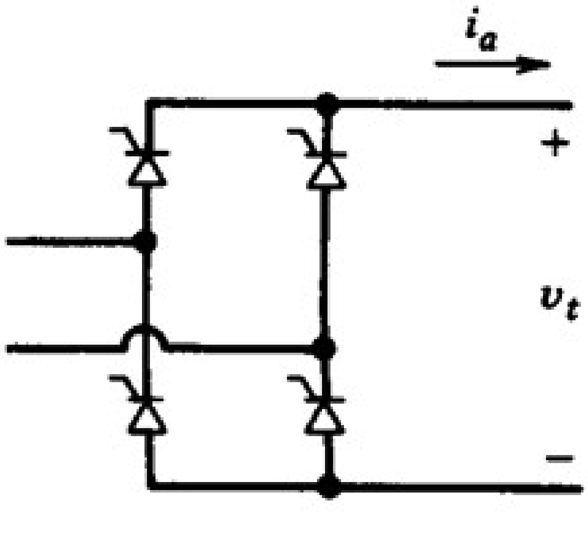


Figure 13-15 Line-frequency-controlled converters for dc motor drives: (*a*) single-phase input; (*b*) three-phase input.

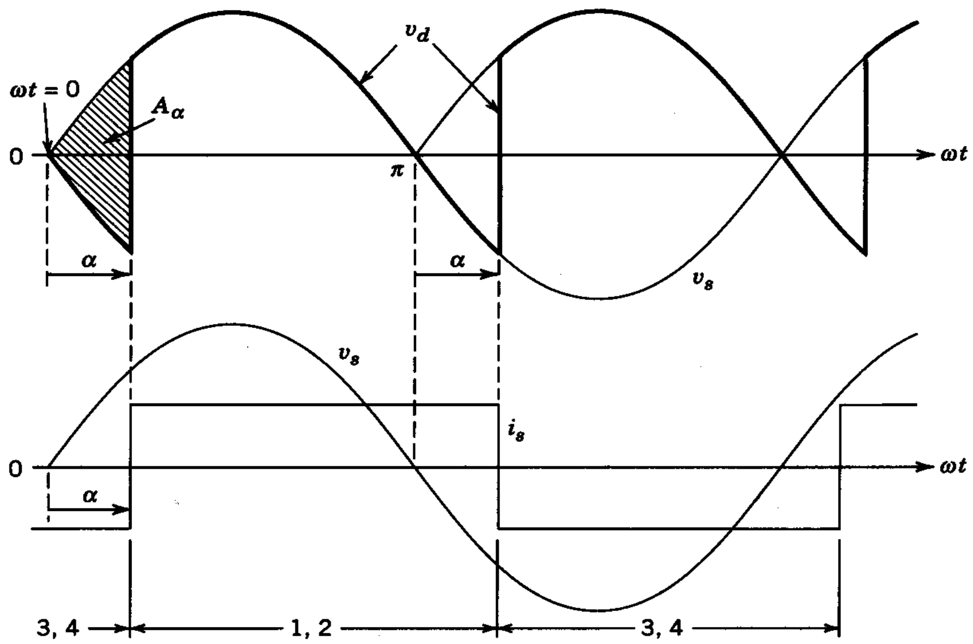
Adjustable-speed DC Drives

13.6.2 Line-frequency controlled converter

- A disadvantage of the line-frequency converters is the longer response to the speed control signals (due to fire delay angle), compared to high frequency switch-mode dc-dc converters.



(a)



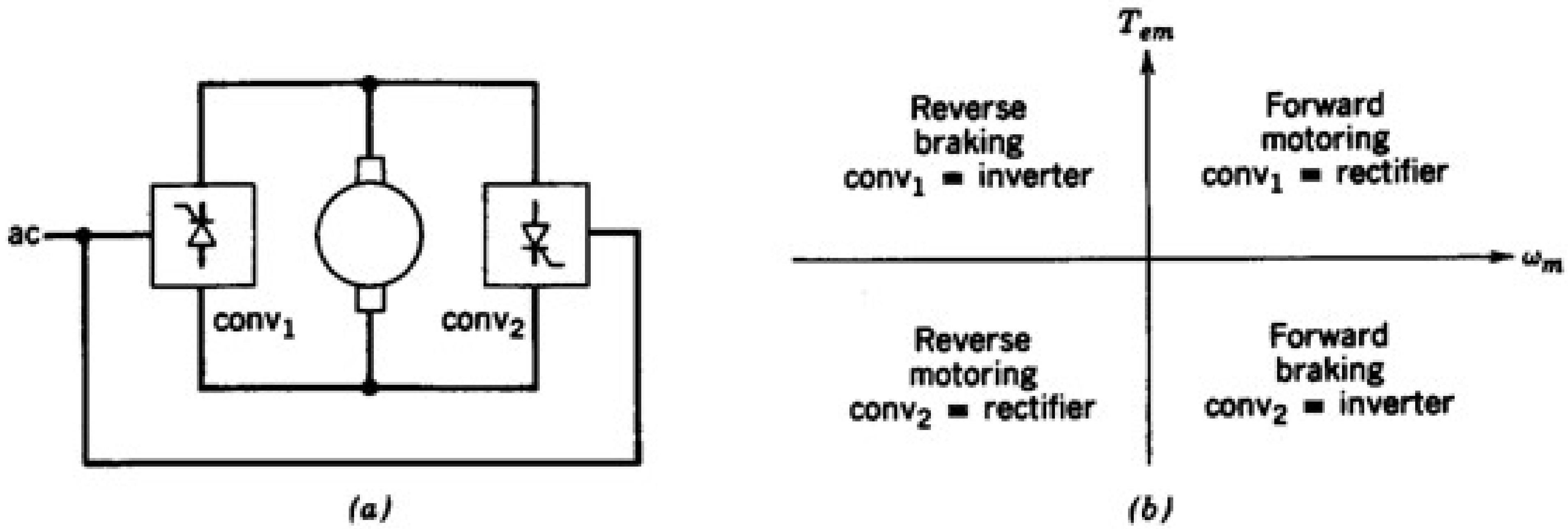
(b) α = finite

Adjustable-speed DC Drives

13.6.2 Line-frequency controlled converter

Four-quadrant operation

Two back-to-back connected thyristor converters

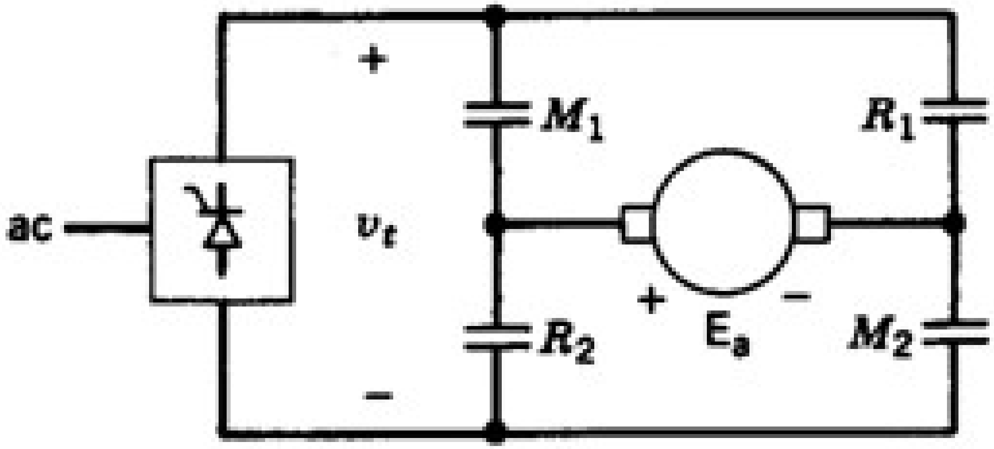


Adjustable-speed DC Drives

13.6.2 Line-frequency controlled converter

Four-quadrant operation

- Two back-to-back connected thyristor converters
- One phase-controlled converter together with two pairs of contactors.



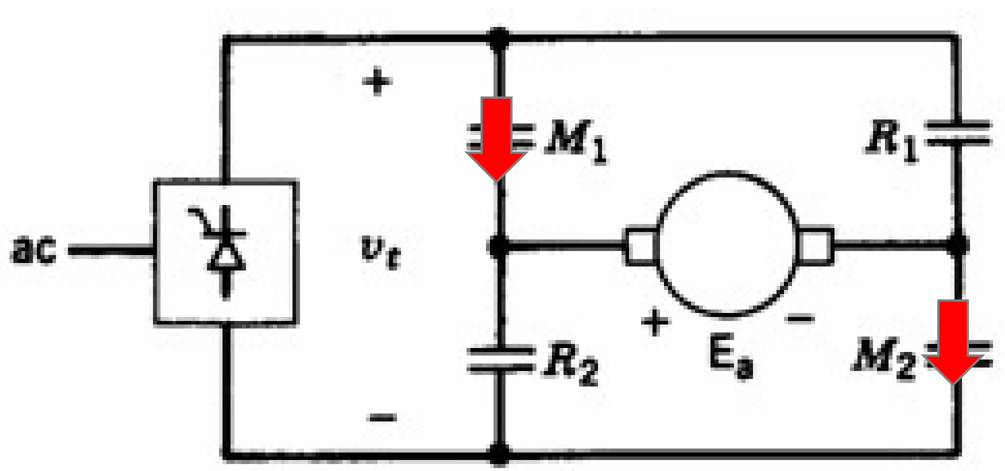
(c)

Adjustable-speed DC Drives

13.6.2 Line-frequency controlled converter

Four-quadrant operation

- Two back-to-back connected thyristor converters
- One phase-controlled converter together with two pairs of contactors.



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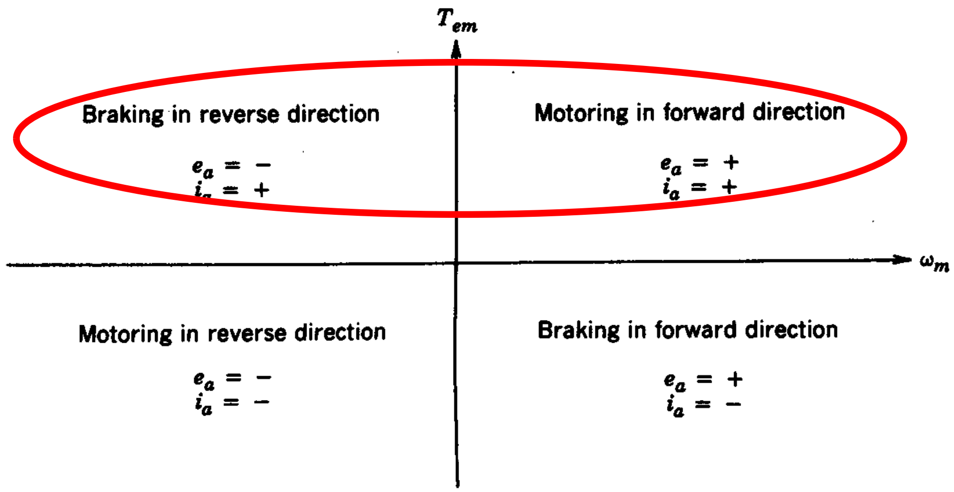


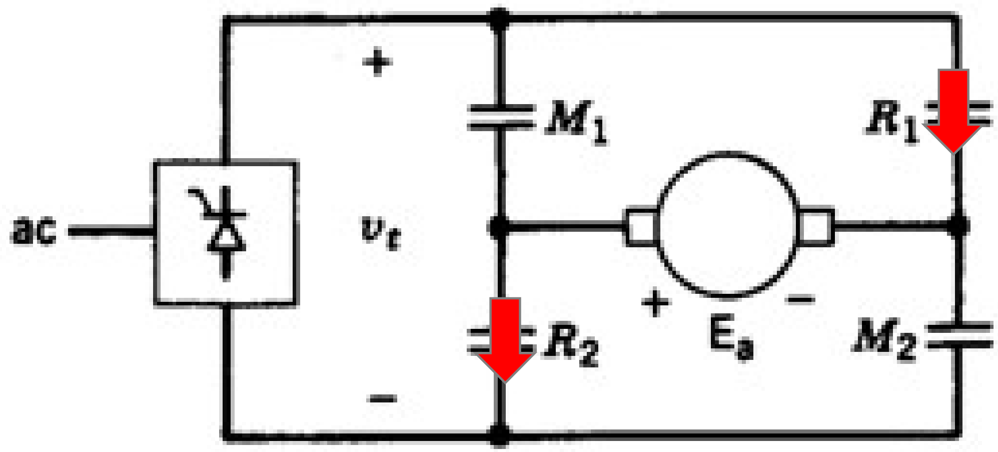
Figure 13-3 Four-quadrant operation of a dc motor.

Adjustable-speed DC Drives

13.6.2 Line-frequency controlled converter

Four-quadrant operation

- Two back-to-back connected thyristor converters
- One phase-controlled converter together with two pairs of contactors.



(c)

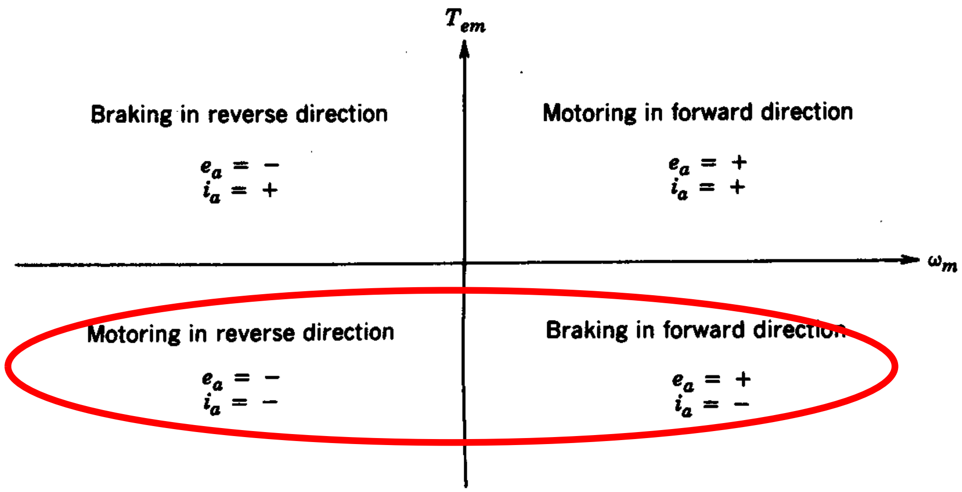
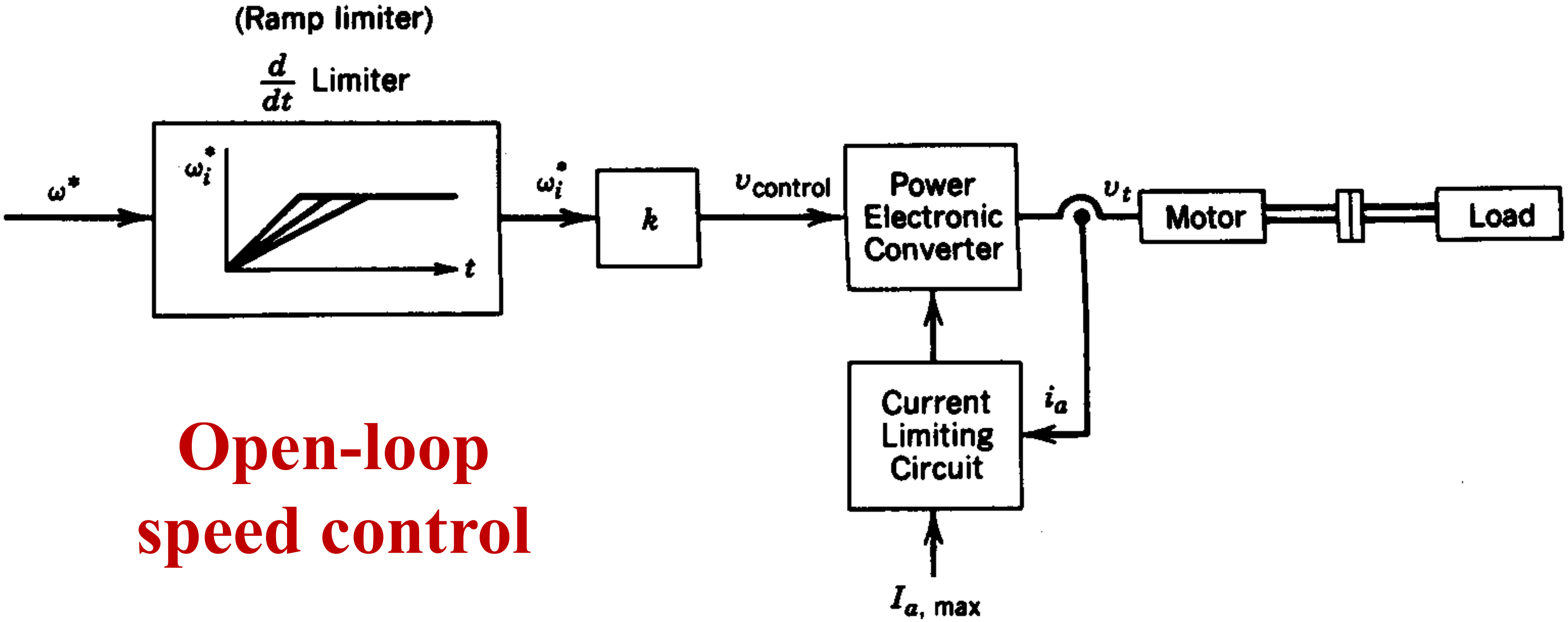


Figure 13-3 Four-quadrant operation of a dc motor.

Adjustable-speed DC Drives

13.6.4 Control of adjustable-speed drives

- A d/dt limiter allows the speed command to change slowly, thus preventing the rotor current from exceeding its rating.



Open-loop speed control

Figure 13-18 Open-loop speed control.

Adjustable-speed DC Drives

13.6.5 Field weakening in adjustable-speed dc motor drives

- The operation higher than the rated speed of the dc motor can be realized by reducing the field flux ϕ_f . A line-frequency controlled converter is normally used to control I_f through the field winding.

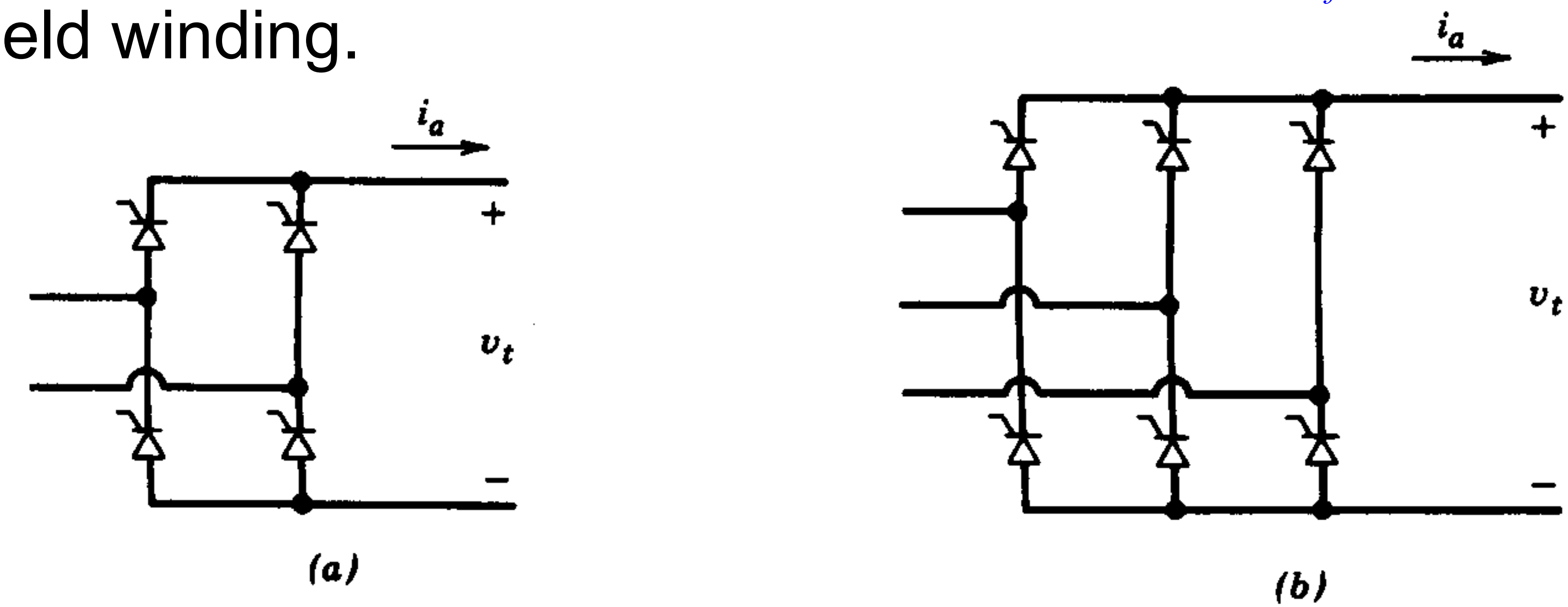


Figure 13-15 Line-frequency-controlled converters for dc motor drives: (*a*) single-phase input; (*b*) three-phase input.

Summary

1. Because of mechanical contact between the commutator segments and brushes, dc motors require periodic maintenance.
2. The magnitude of the electromagnetic torque is directly proportional to the field flux and the armature current magnitude. This makes a dc motor ideal for servo drive applications.
3. The induced back-emf across the armature-winding terminals is proportional to the field flux magnitude and the rotational speed of the motor.
4. The dc motor drives utilize either the line-frequency controlled converters or the dc-dc switch-mode converters. By field weakening in a wound-field dc motor, the speed can be controlled beyond its rated value, without exceeding the rated armature voltage.

Chap.13 DC Motor Drives

Vocabulary

1.armature winding	n.	电枢绕组
2.commutator	n.	换向器
3.carbon brushes	n.	碳刷
4.back-emf	n.	反电势
5.kinetic energy	n.	动能
6.servo drives	n.	伺服传动
7.adjustable speed drives	n.	变频调速
8.wound-field motor	n.	绕线磁场式电动机