Chapter 8

Switch-Mode DC-AC Inverters

- converters for ac motor drives and uninterruptible power supplies

Switch-Mode DC-AC Inverter

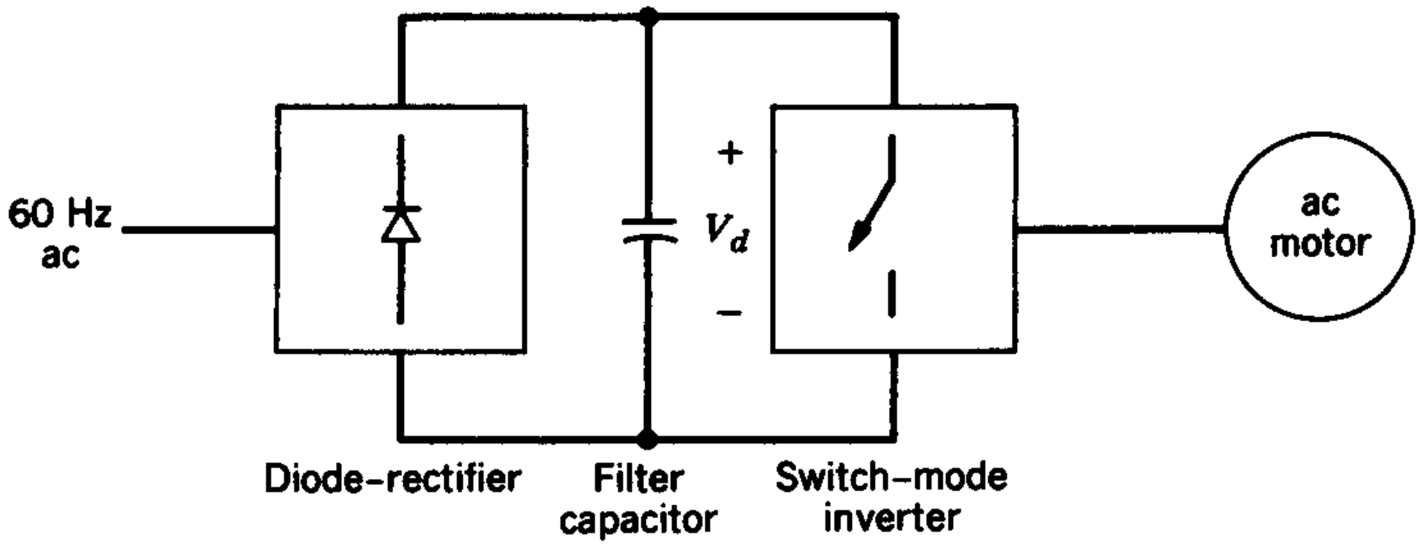

Figure 8-1 Switch-mode inverter in ac motor drive.

- Block diagram of a motor drive where the power flow is unidirectional

Switch-Mode DC-AC Inverter

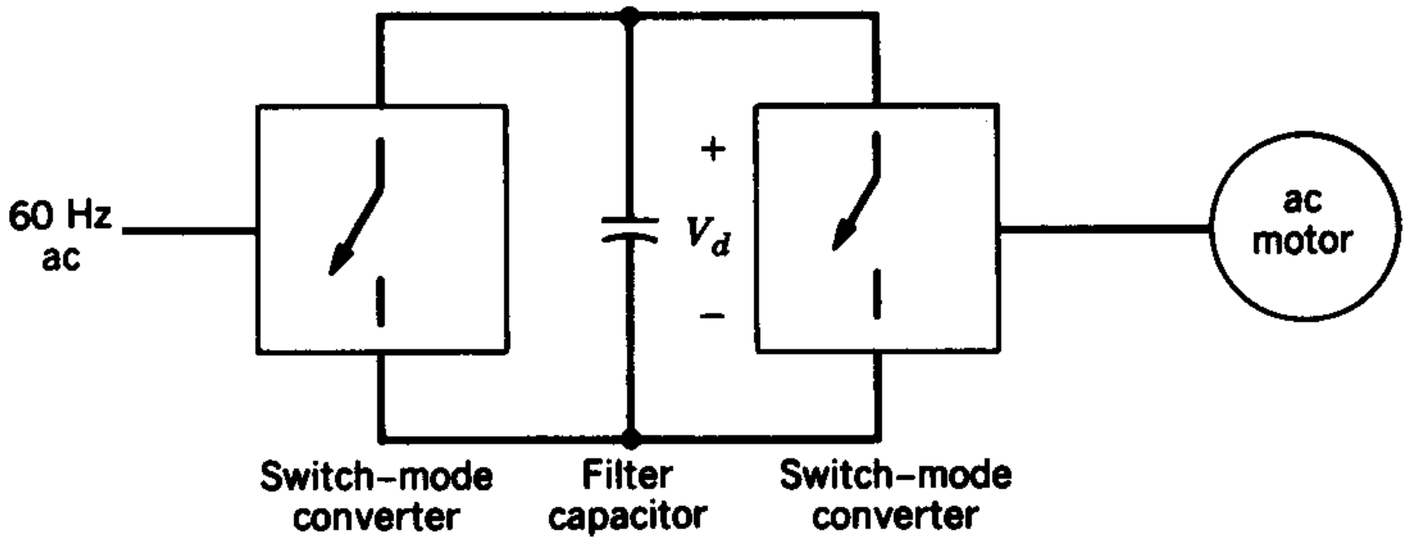

Figure 8-2 Switch-mode converters for motoring and regenerative braking in ac motor drive.

- Block diagram of a motor drive where the power flow can be bi-directional

Switch-Mode DC-AC Inverter

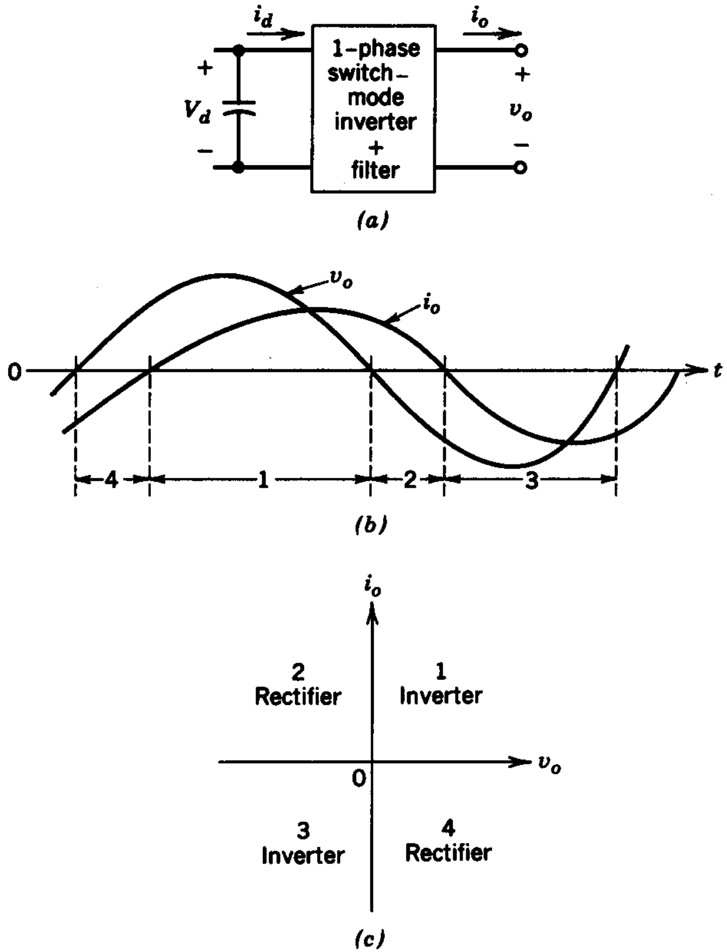

Figure 8-3 Single-phase switch-mode inverter.

- Four quadrants of operation

One Leg of a Switch-Mode DC-AC Inverter

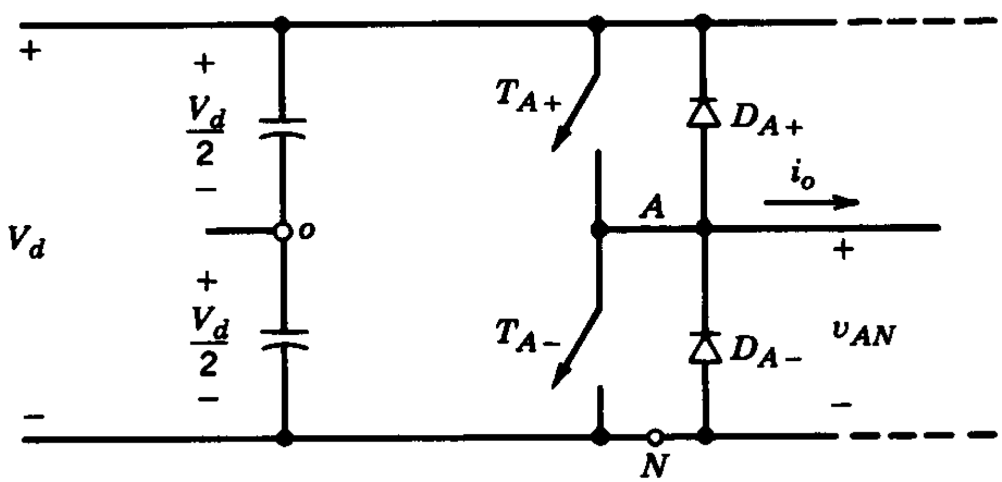

Figure 8-4 One-leg switch-mode inverter.

- The mid-point shown is fictitious

Synthesis of a Sinusoidal Output by PWM

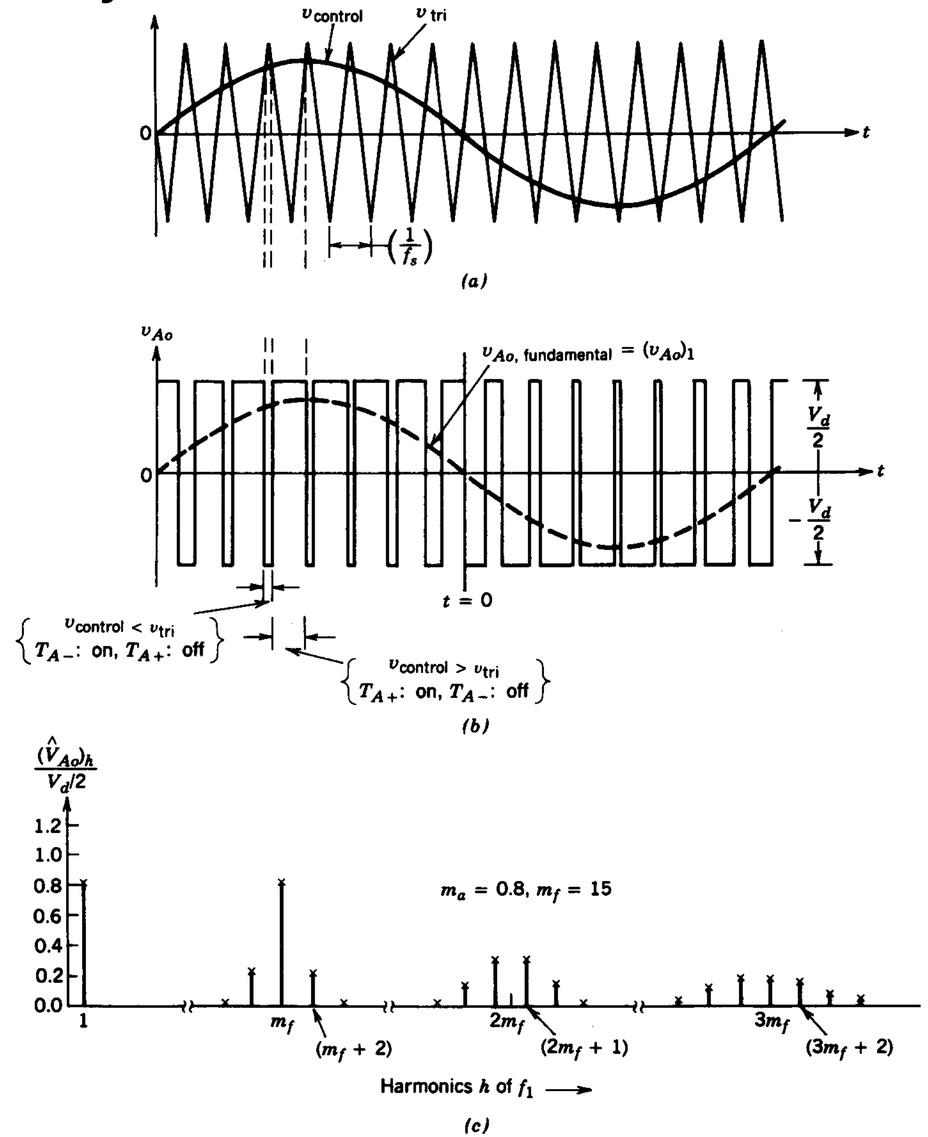

Figure 8-5 Pulse-width modulation.

Details of a Switching Time Period

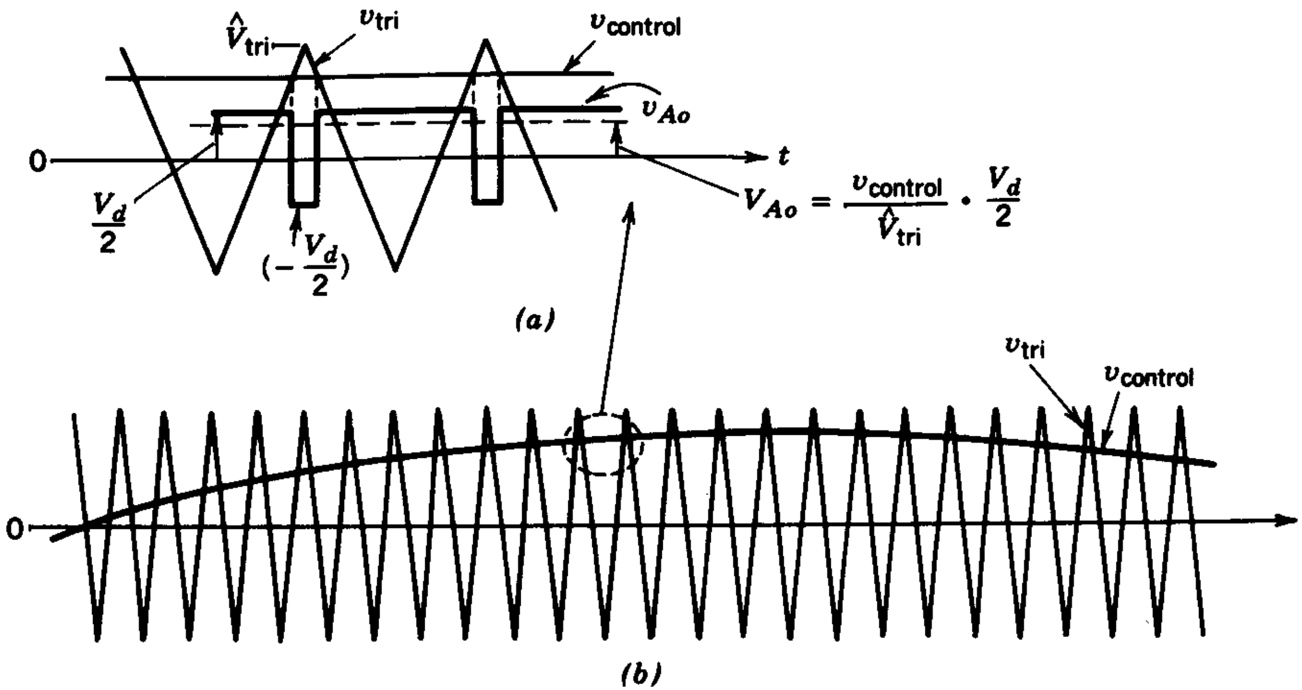

Figure 8-6 Sinusoidal PWM.

- Control voltage can be assumed constant during a switching time-period

Harmonics in the DC-AC Inverter Output Voltage

Table 8-1 Generalized Harmonics of v_{Ao} for a Large m_f.

h \ m_a	0.2	0.4	0.6	0.8	1.0
1 Fundamental	0.2	0.4	0.6	0.8	1.0
m_f	1.242	1.15	1.006	0.818	0.601
$m_f \pm 2$	0.016	0.061	0.131	0.220	0.318
$m_f \pm 4$					0.018
$2m_f \pm 1$	0.190	0.326	0.370	0.314	0.181
$2m_f \pm 3$		0.024	0.071	0.139	0.212
$2m_f \pm 5$				0.013	0.033
$3m_f$	0.335	0.123	0.083	0.171	0.113
$3m_f \pm 2$	0.044	0.139	0.203	0.176	0.062
$3m_f \pm 4$		0.012	0.047	0.104	0.157
$3m_f \pm 6$				0.016	0.044
$4m_f \pm 1$	0.163	0.157	0.008	0.105	0.068
$4m_f \pm 3$	0.012	0.070	0.132	0.115	0.009
$4m_f \pm 5$			0.034	0.084	0.119
$4m_f \pm 7$				0.017	0.050

Note: $(\hat{V}_{Ao})_h / \frac{1}{2}V_d$ [$= (\hat{V}_{AN})_h / \frac{1}{2}V_d$] is tabulated as a function of m_a.

- Harmonics appear around the carrier frequency and its multiples

Harmonics due to Over-modulation

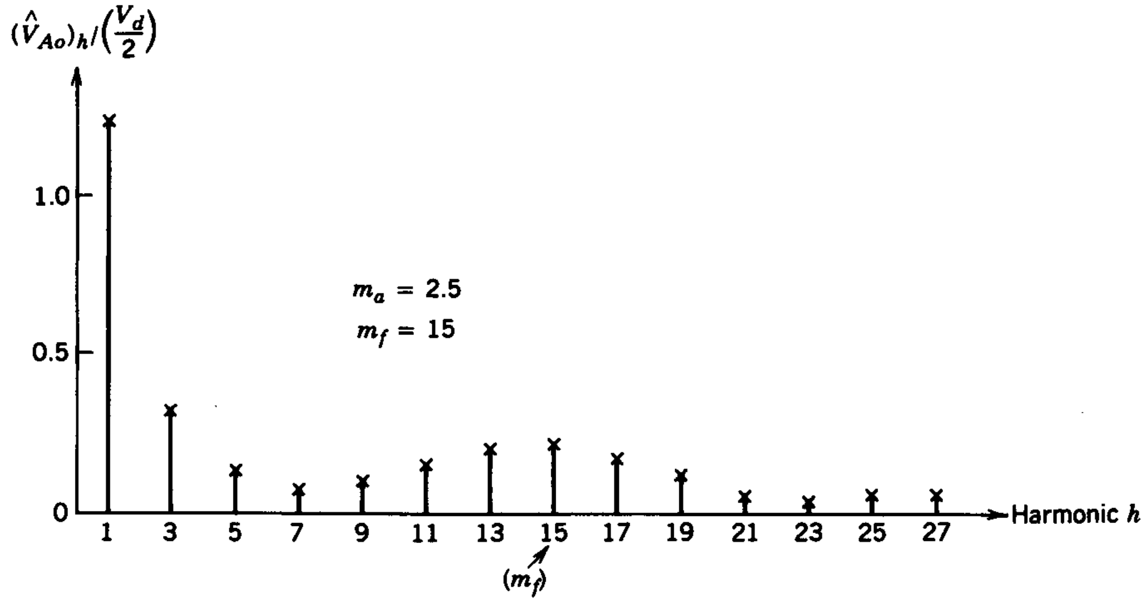

Figure 8-7 Harmonics due to overmodulation; drawn for $m_a = 2.5$ and $m_f = 15$.

- These are harmonics of the fundamental frequency

Output voltage Fundamental as a Function of the Modulation Index

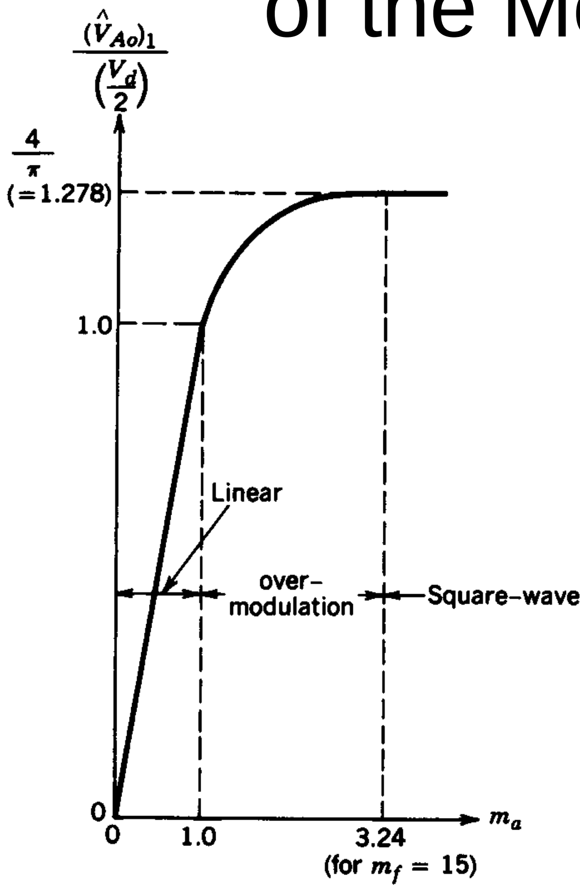

Figure 8-8 Voltage control by varying m_a.

- Shows the linear and the over-modulation regions; square-wave operation in the limit

Square-Wave Mode of Operation

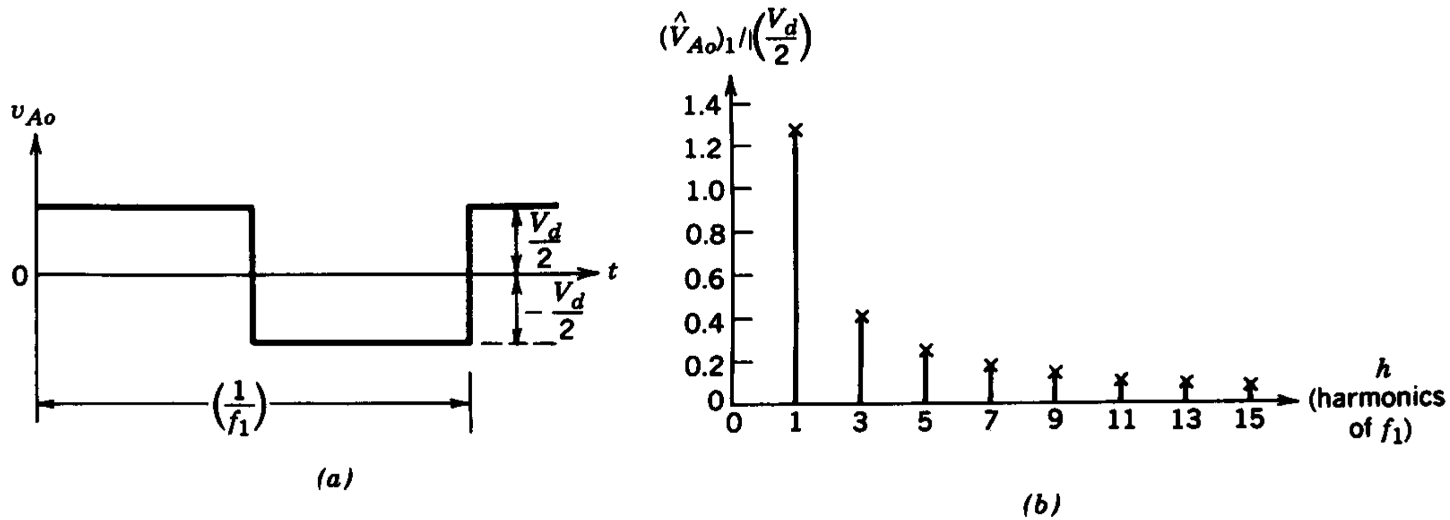

Figure 8-9 Square-wave switching.

- Harmonics are of the fundamental frequency

Half-Bridge Inverter

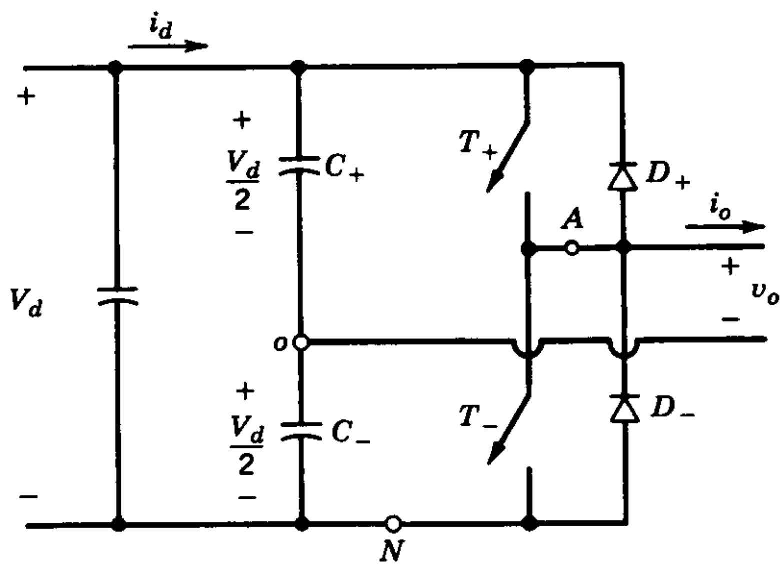

Figure 8-10 Half-bridge inverter.

- Capacitors provide the mid-point

Single-Phase Full-Bridge DC-AC Inverter

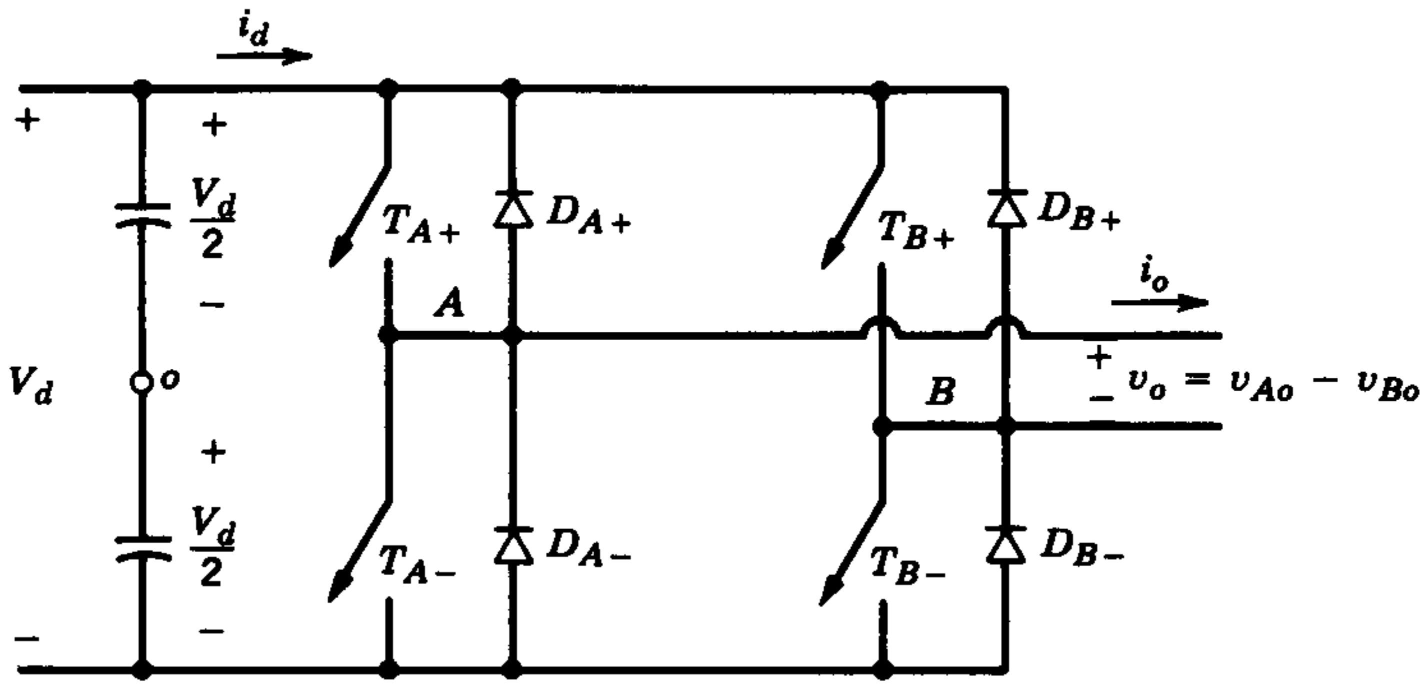

Figure 8-11 Single-phase full-bridge inverter.

- Consists of two inverter legs

PWM to Synthesize Sinusoidal Output

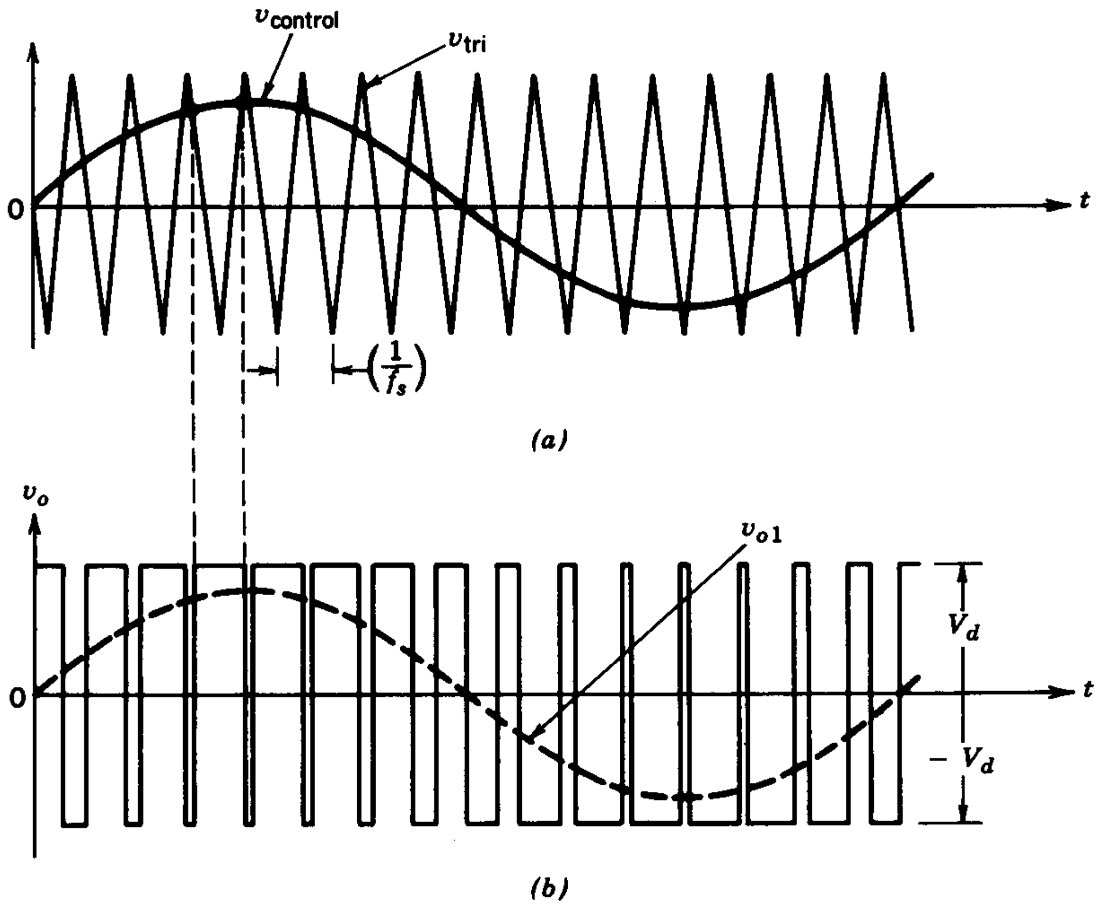

Figure 8-12 PWM with bipolar voltage switching.

• The dotted curve is the desired output; also the fundamental frequency

Analysis assuming Fictitious Filters

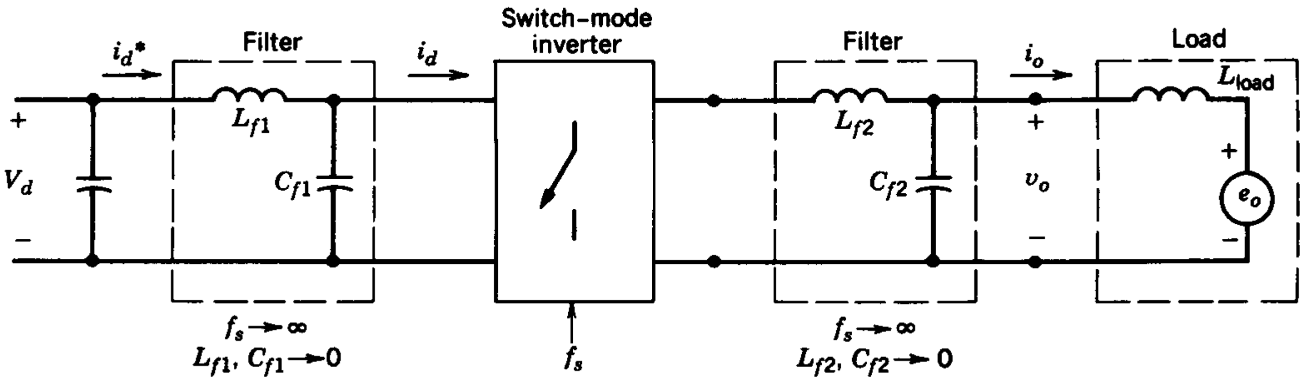

Figure 8-13 Inverter with "fictitious" filters.

• Small fictitious filters eliminate the switching-frequency related ripple

DC-Side Current

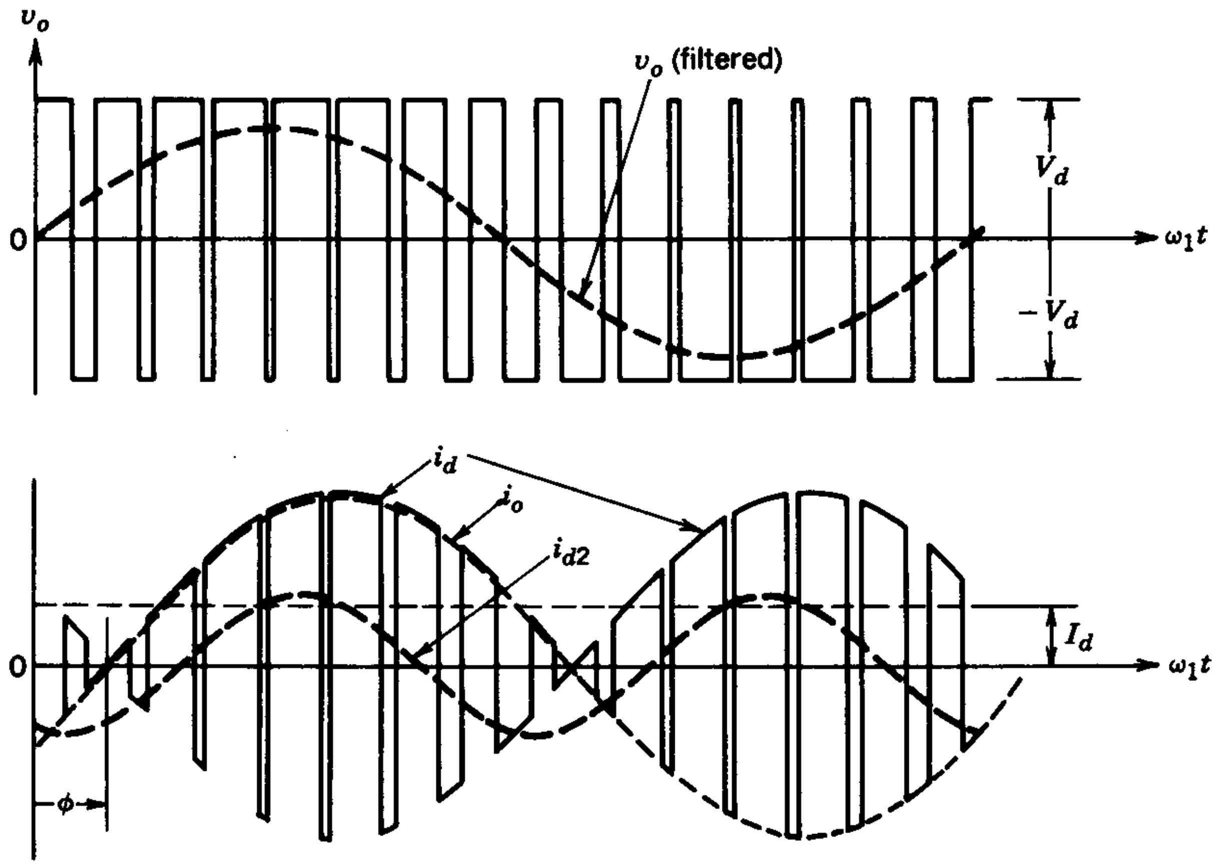

Figure 8-14 The dc-side current in a single-phase inverter with PWM bipolar voltage switching.

- Bi-Polar Voltage switching

Output Waveforms: Uni-polar Voltage Switching

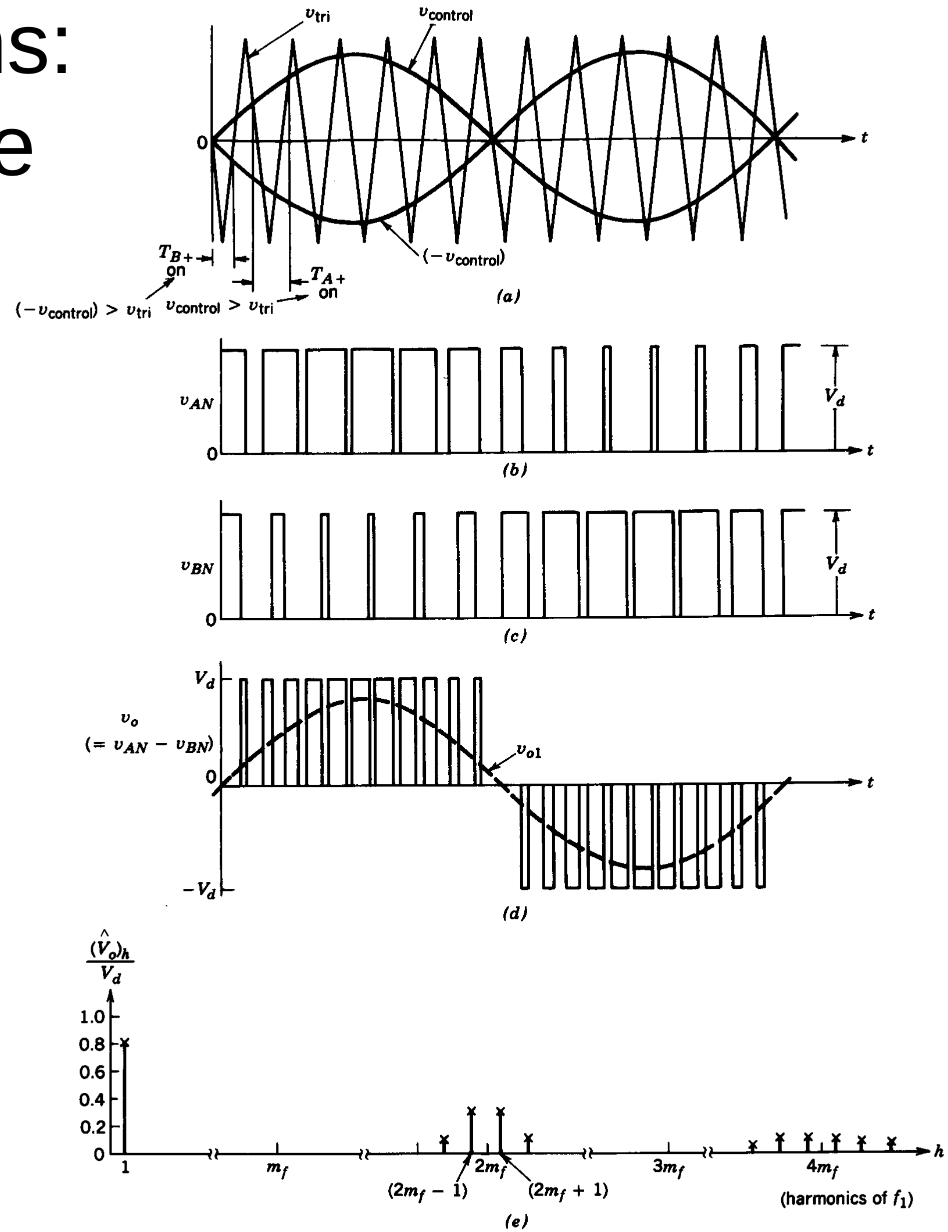

Figure 8-15 PWM with unipolar voltage switching (single phase).

- Harmonic components around the switching frequency are absent

DC-Side Current in a Single-Phase Inverter

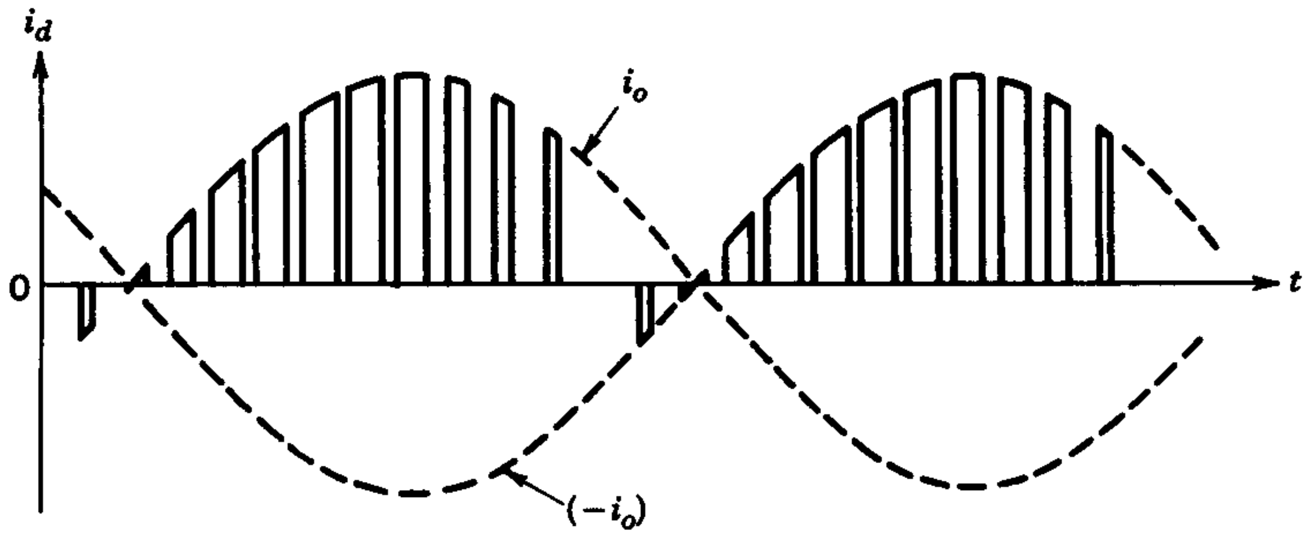

Figure 8-16 The dc-side current in a single-phase inverter with PWM unipolar voltage switching.

- Uni-polar voltage switching

Sinusoidal Synthesis by Voltage Shift

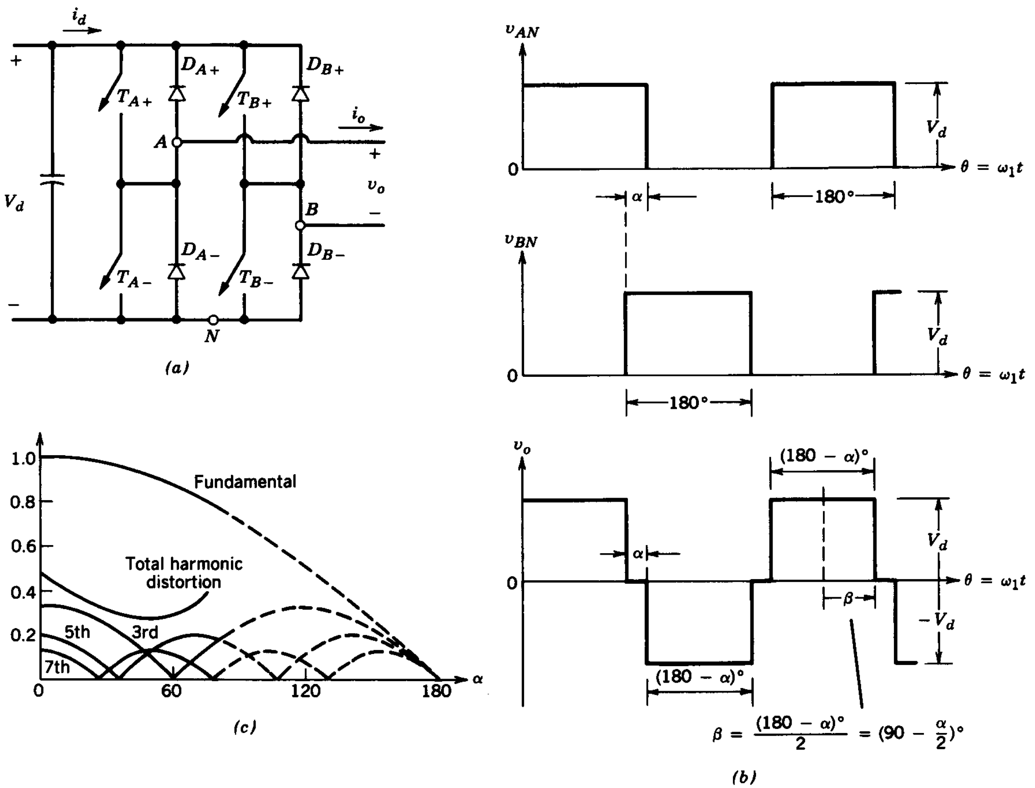

Figure 8-17 Full-bridge, single-phase inverter control by voltage cancellation: (*a*) power circuit; (*b*) waveforms; (*c*) normalized fundamental and harmonic voltage output and total harmonic distortion as a function of α.

- Phase shift allows voltage cancellation to synthesize a 1-Phase sinusoidal output

Single-Phase Inverter

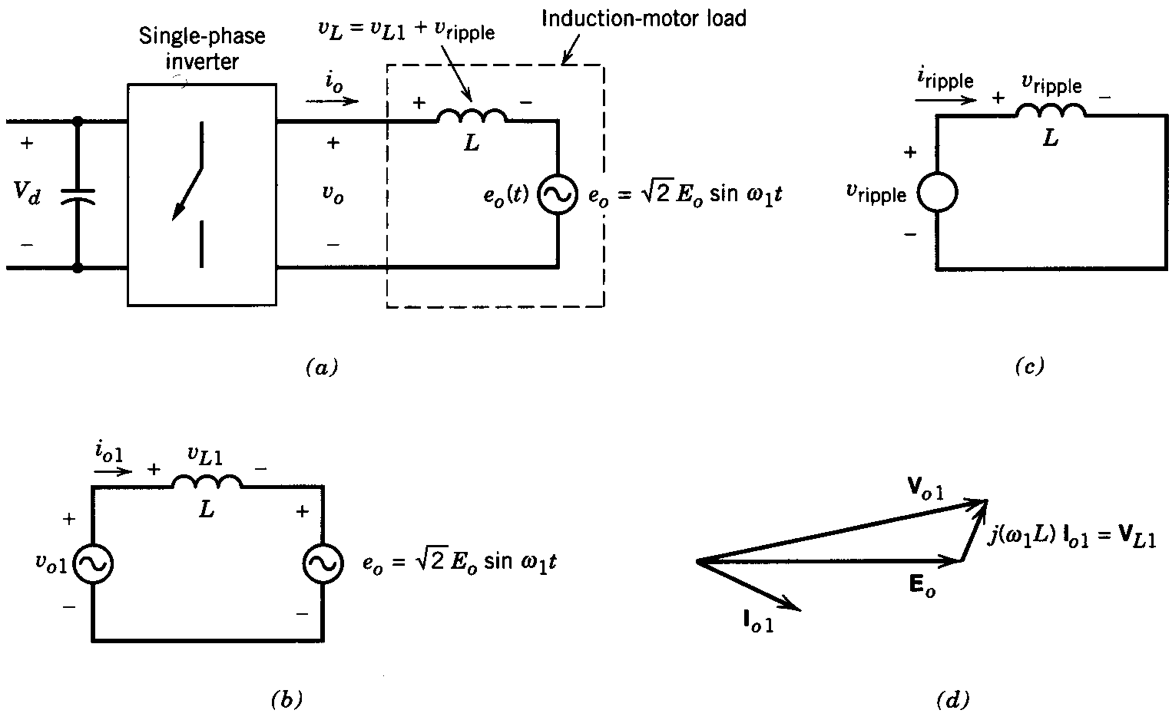

Figure 8-18 Single-phase inverter: (*a*) circuit; (*b*) fundamental-frequency components; (*c*) ripple frequency components; (*d*) fundamental-frequency phasor diagram.

- Analysis at the fundamental frequency

Square-Wave and PWM Operation

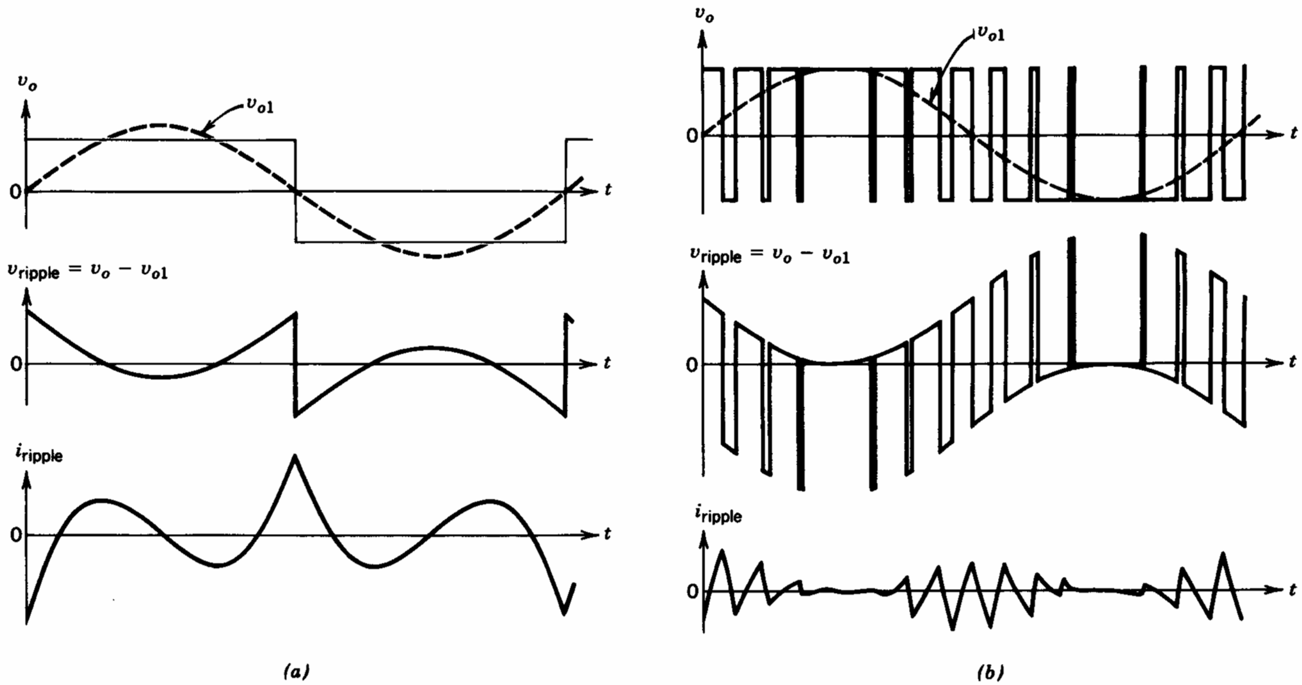

Figure 8-19 Ripple in the inverter output: (*a*) square-wave switching; (*b*) PWM bipolar voltage switching.

- PWM results in much smaller ripple current

Push-Pull Inverter

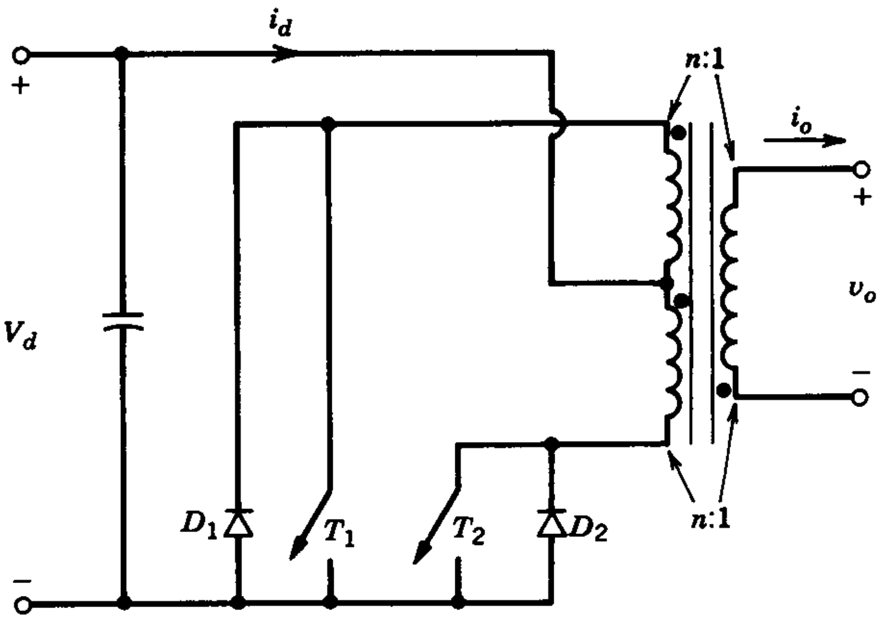

Figure 8-20 Push–pull inverter (single phase).

- Low Voltage to higher output using square-wave operation

Three-Phase Inverter

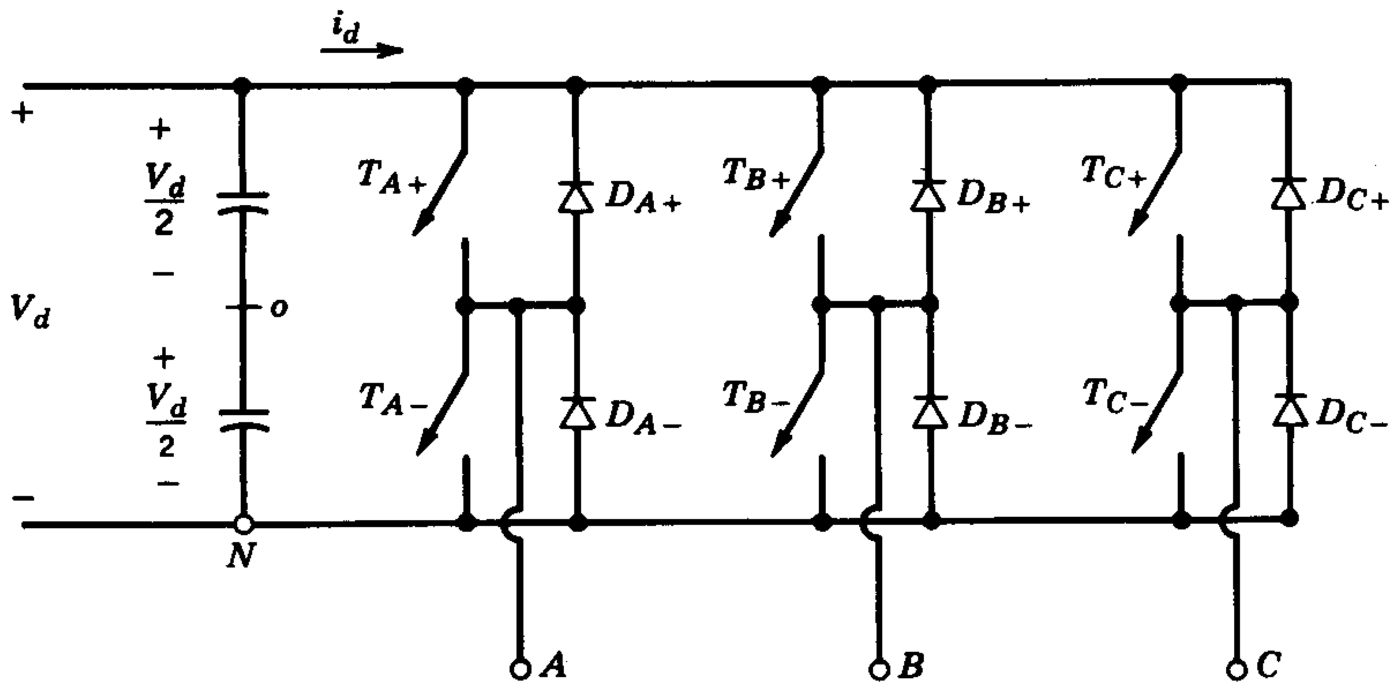

Figure 8-21 Three-phase inverter.

- Three inverter legs; capacitor mid-point is fictitious

Three-Phase PWM Waveforms

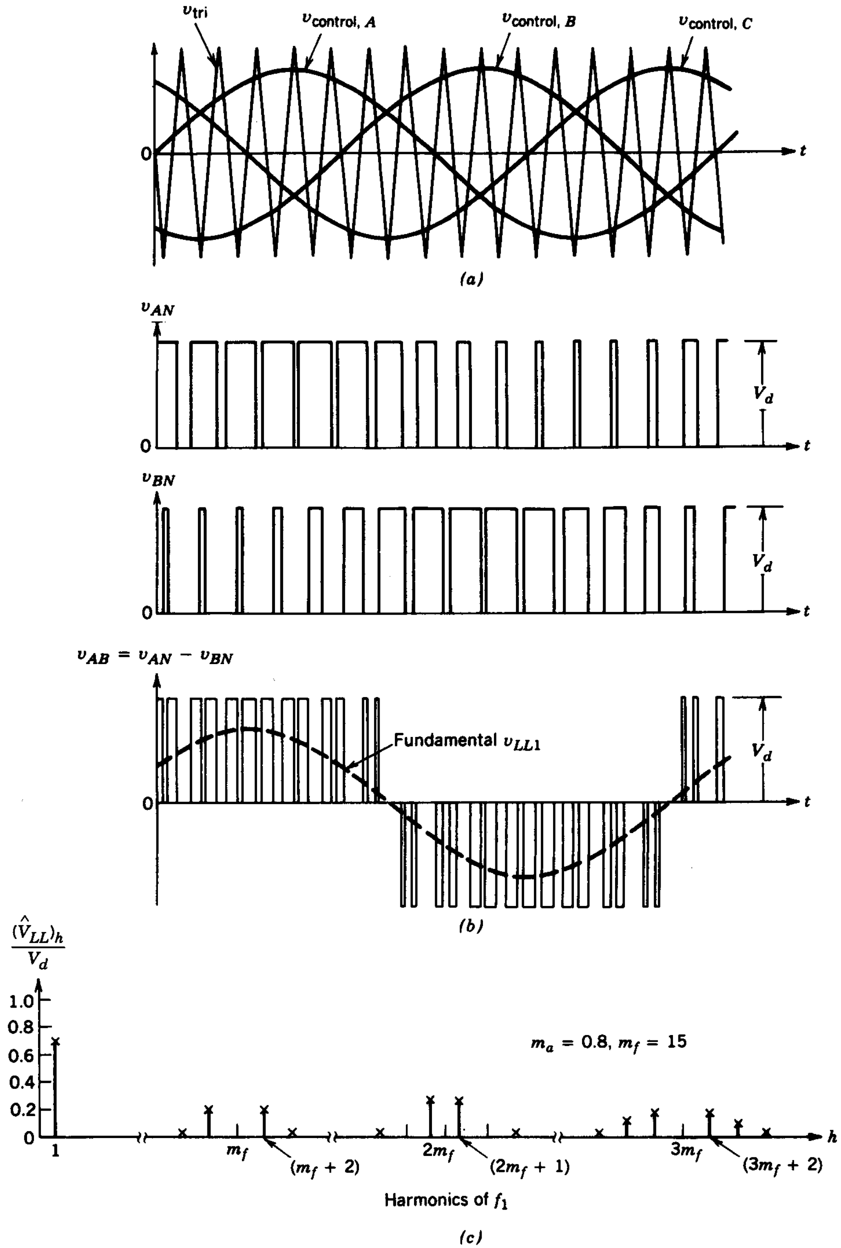

Figure 8-22 Three-phase PWM waveforms and harmonic spectrum.

Three-Phase Inverter Harmonics

Table 8-2 Generalized Harmonics of v_{LL} for a Large and Odd m_f That Is a Multiple of 3.

h \ m_a	0.2	0.4	0.6	0.8	1.0
1	0.122	0.245	0.367	0.490	0.612
$m_f \pm 2$	0.010	0.037	0.080	0.135	0.195
$m_f \pm 4$				0.005	0.011
$2m_f \pm 1$	0.116	0.200	0.227	0.192	0.111
$2m_f \pm 5$				0.008	0.020
$3m_f \pm 2$	0.027	0.085	0.124	0.108	0.038
$3m_f \pm 4$		0.007	0.029	0.064	0.096
$4m_f \pm 1$	0.100	0.096	0.005	0.064	0.042
$4m_f \pm 5$			0.021	0.051	0.073
$4m_f \pm 7$				0.010	0.030

Note: $(V_{LL})_h/V_d$ are tabulated as a function of m_a where $(V_{LL})_h$ are the rms values of the harmonic voltages.

Three-Phase Inverter Output

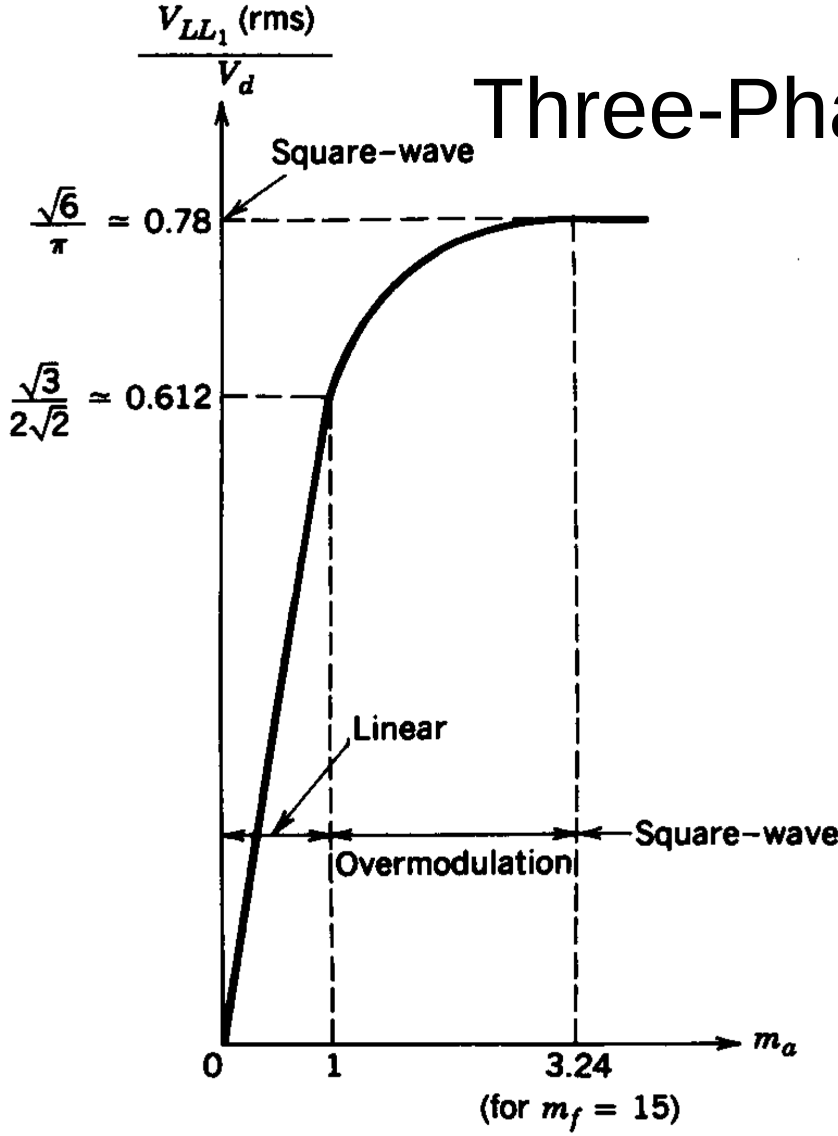

Figure 8-23 Three-phase inverter; V_{LL_1}(rms)/V_d as a function of m_a.

- Linear and over-modulation ranges

Three-Phase Inverter: Square-Wave Mode

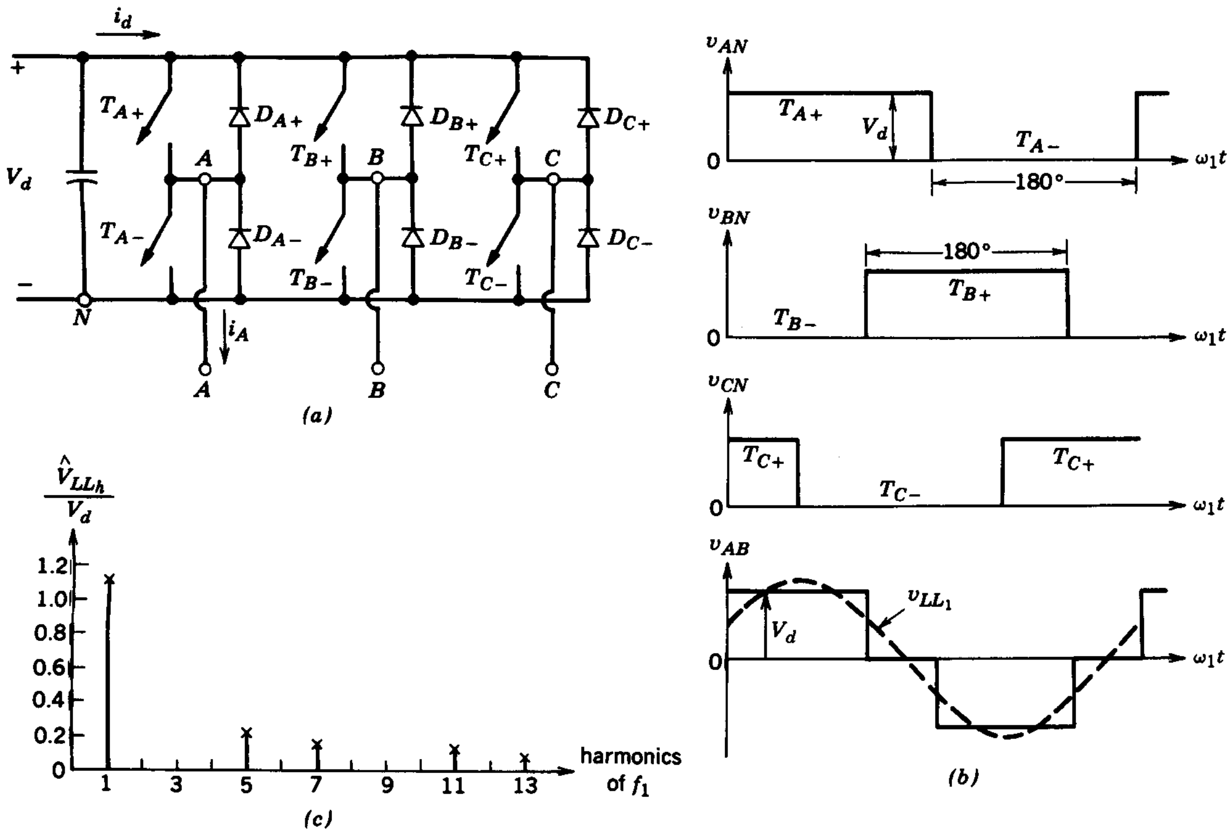

Figure 8-24 Square-wave inverter (three phase).

- Harmonics are of the fundamental frequency

Three-Phase Inverter: Fundamental Frequency

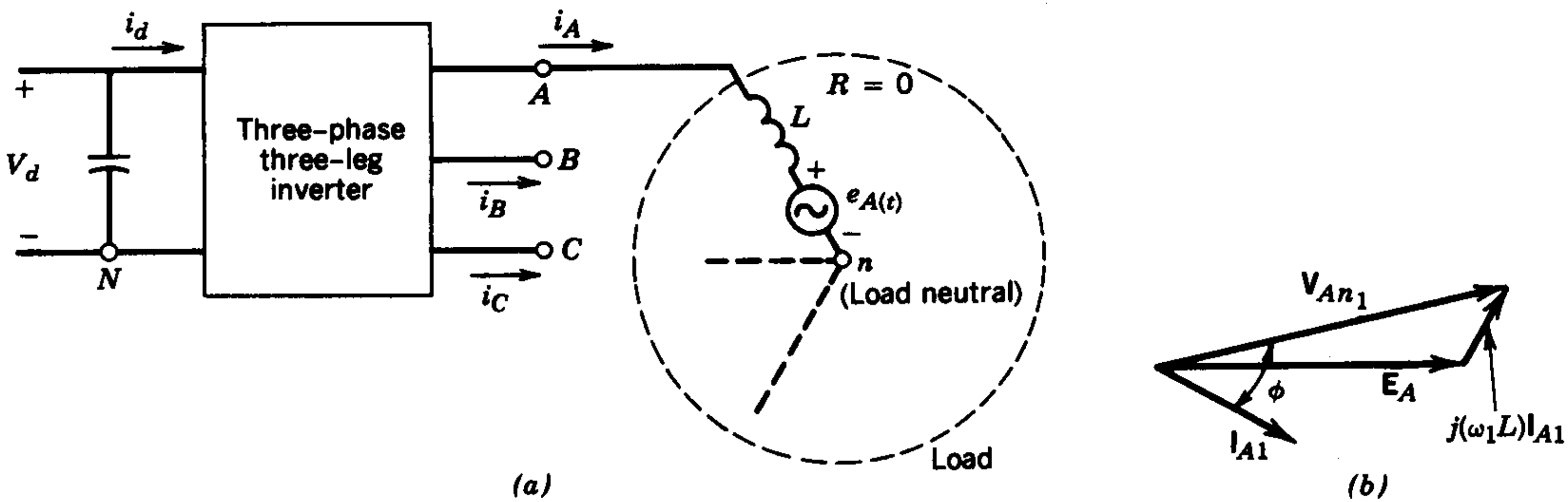

Figure 8-25 Three-phase inverter: (*a*) circuit diagram; (*b*) phasor diagram (fundamental frequency).

- Analysis at the fundamental frequency can be done using phasors

Square-Wave and PWM Operation

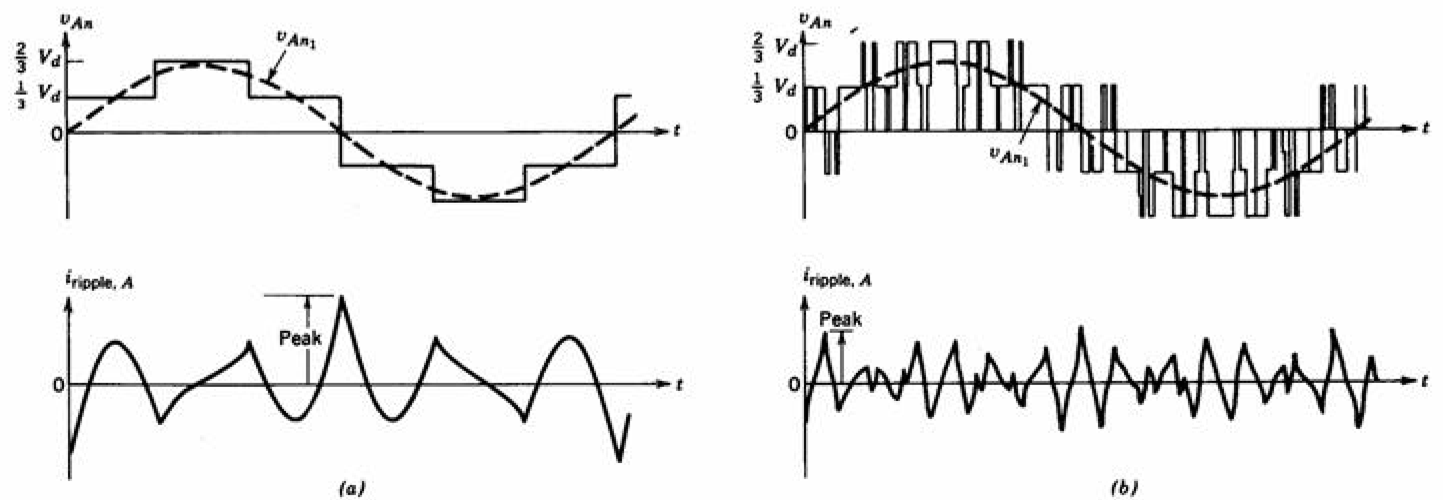

Figure 8-26 Phase-to-load-neutral variables of a three-phase inverter: (*a*) square wave; (*b*) PWM.

- PWM results in much smaller ripple current

DC-Side Current in a Three-Phase Inverter

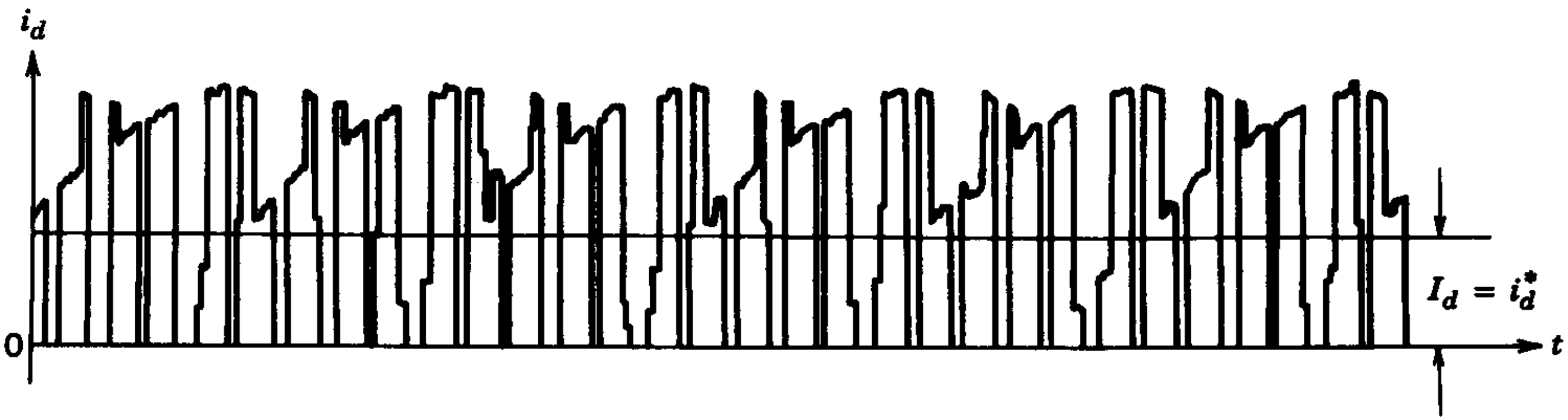

Figure 8-27 Input dc current in a three-phase inverter.

- The current consists of a dc component and the switching-frequency related harmonics

Square-Wave Operation

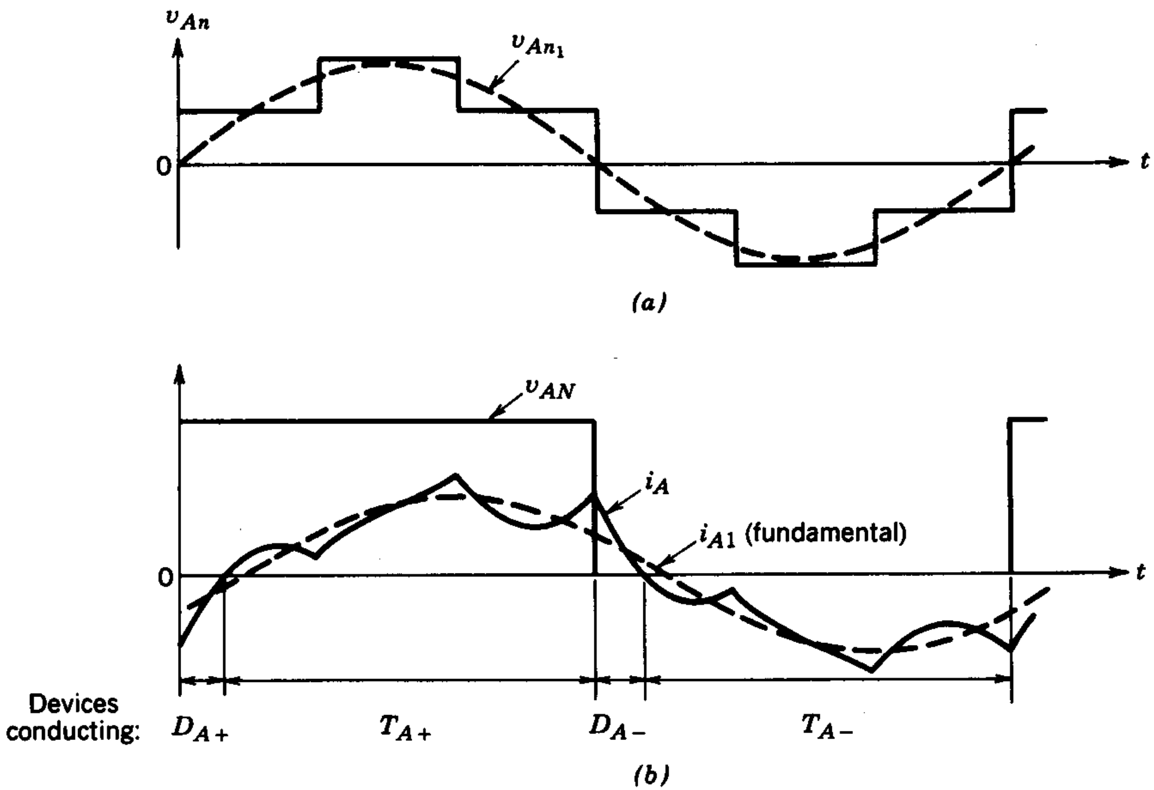

Figure 8-28 Square-wave inverter: phase A waveforms.

- devices conducting are indicated

PWM Operation

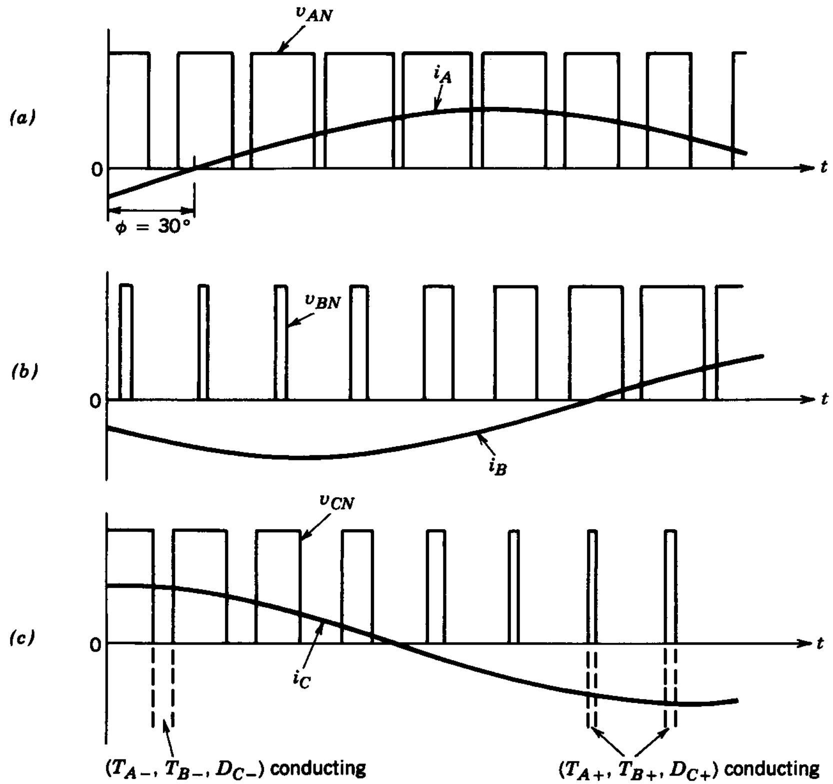

Figure 8-29 PWM inverter waveforms: load power factor angle = 30° (lag).

- devices conducting are indicated

Short-Circuit States in PWM Operation

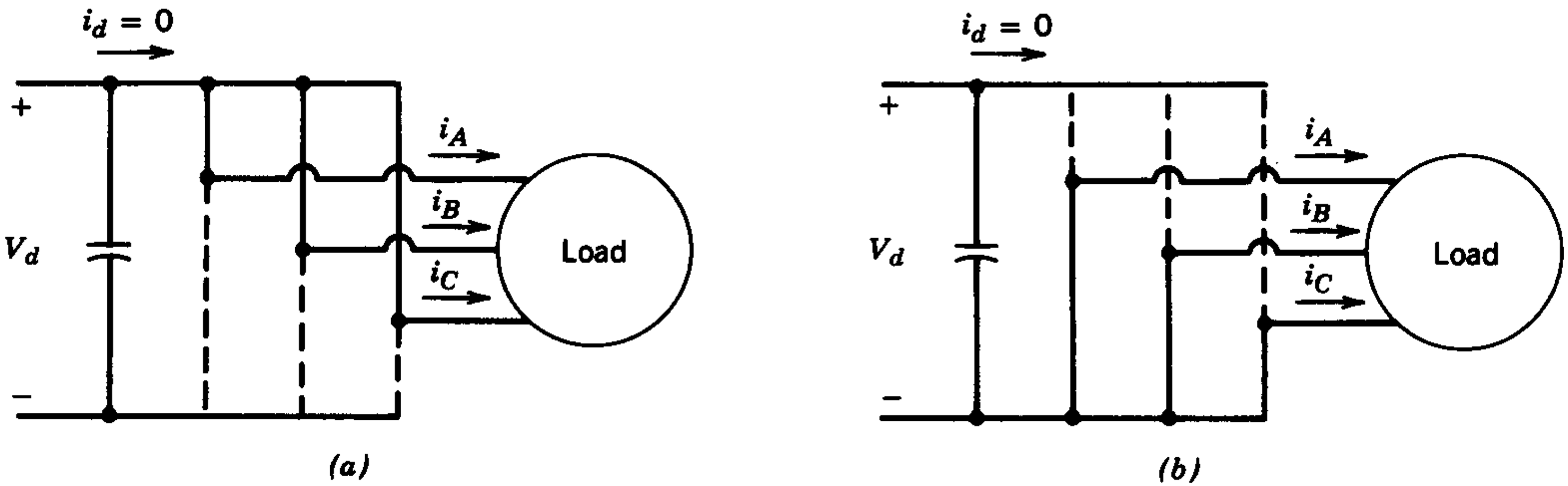

Figure 8-30 Short-circuit states in a three-phase PWM inverter.

• top group or the bottom group results in short circuiting three terminals

Effect of Blanking Time

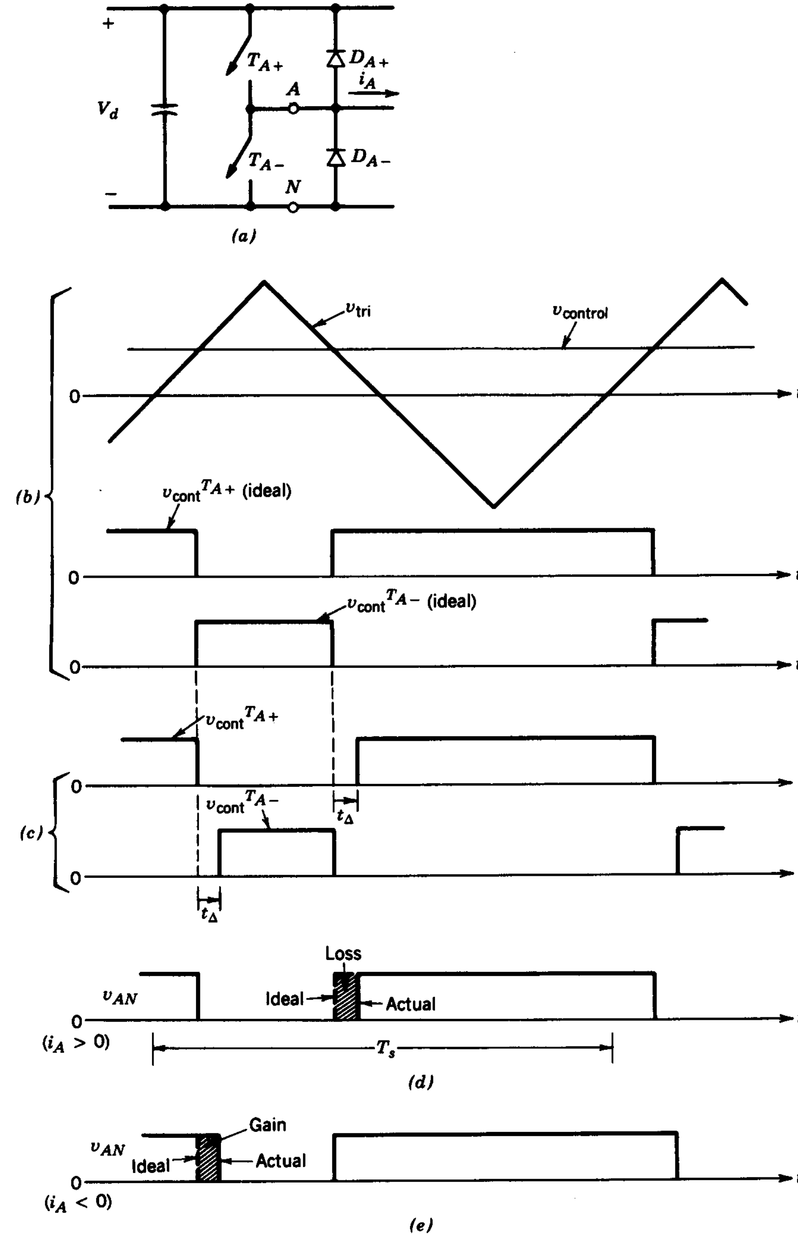

Figure 8-31 Effect of blanking time t_Δ.

- Results in nonlinearity

Effect of Blanking Time

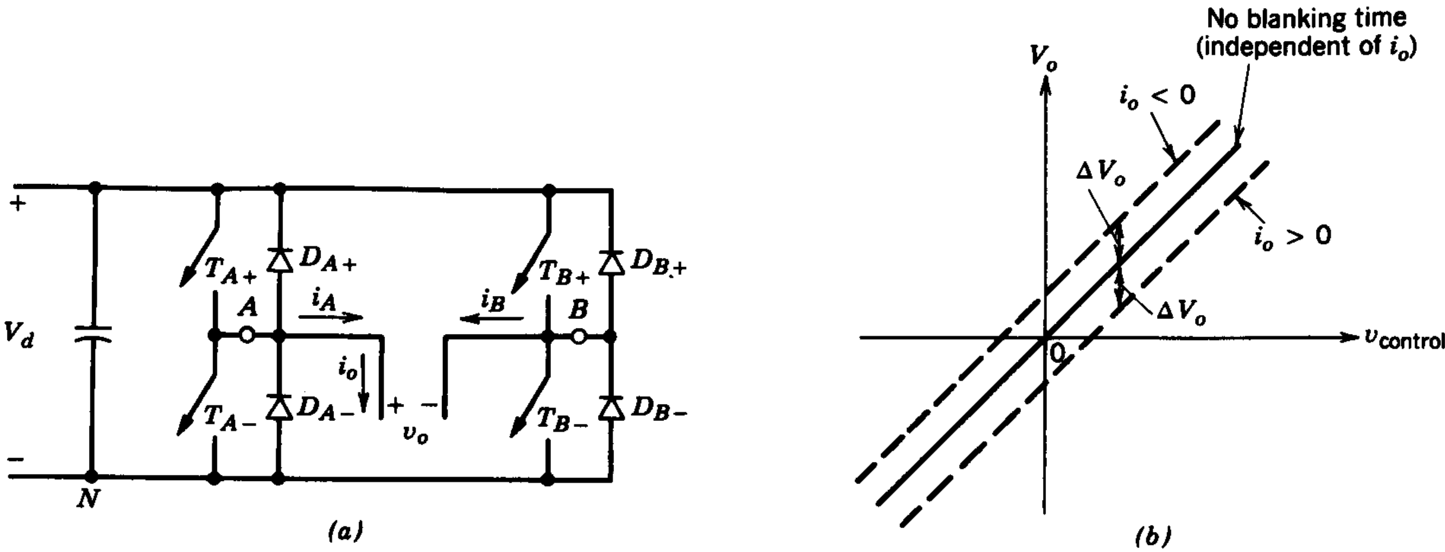

Figure 8-32 Effect of t_Δ on V_o, where ΔV_o is defined as a voltage drop if positive.

- Voltage jump when the current reverses direction

Effect of Blanking Time

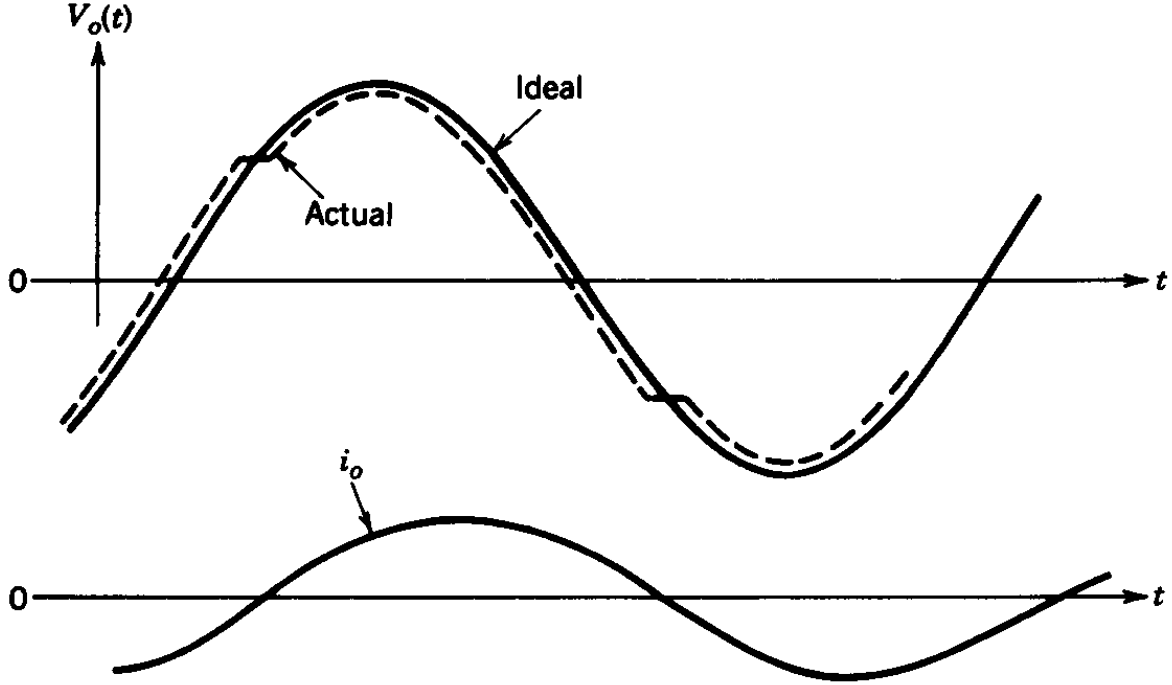

Figure 8-33 Effect of t_Δ on the sinusoidal output.

- Effect on the output voltage

Programmed Harmonic Elimination

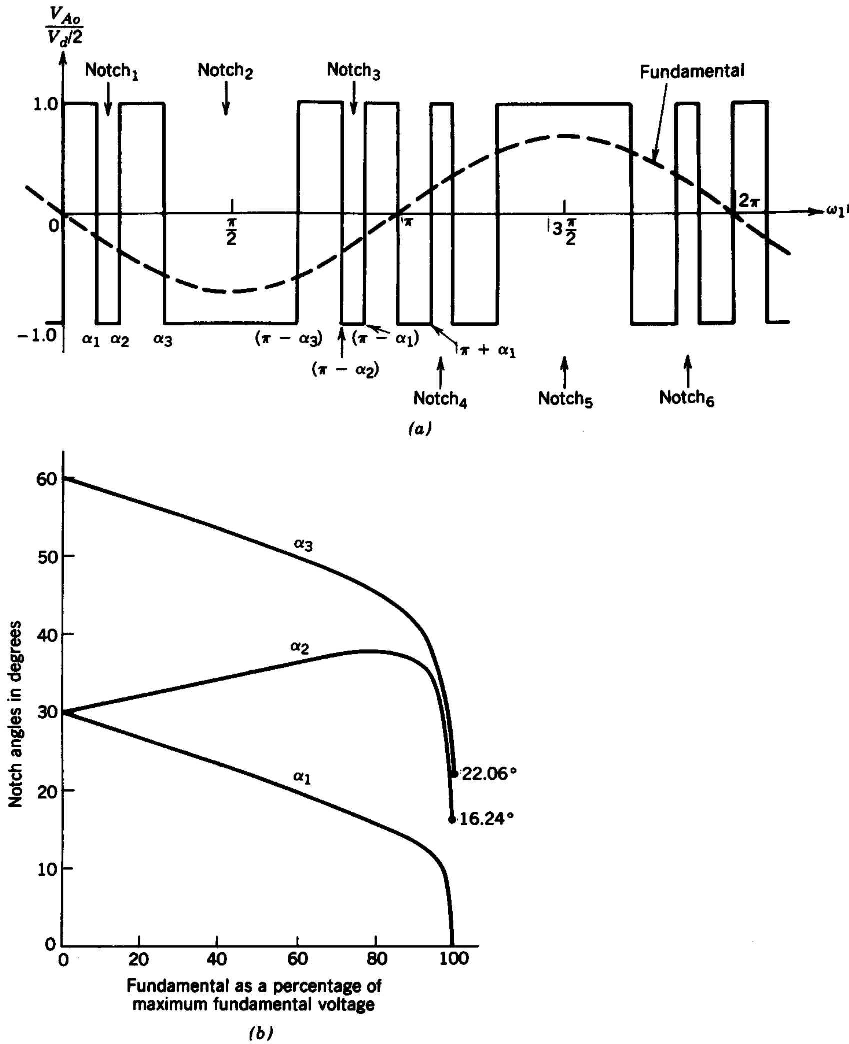

Figure 8-34 Programmed harmonic elimination of fifth and seventh harmonics.

- Angles based on the desired output

Tolerance-Band Current Control

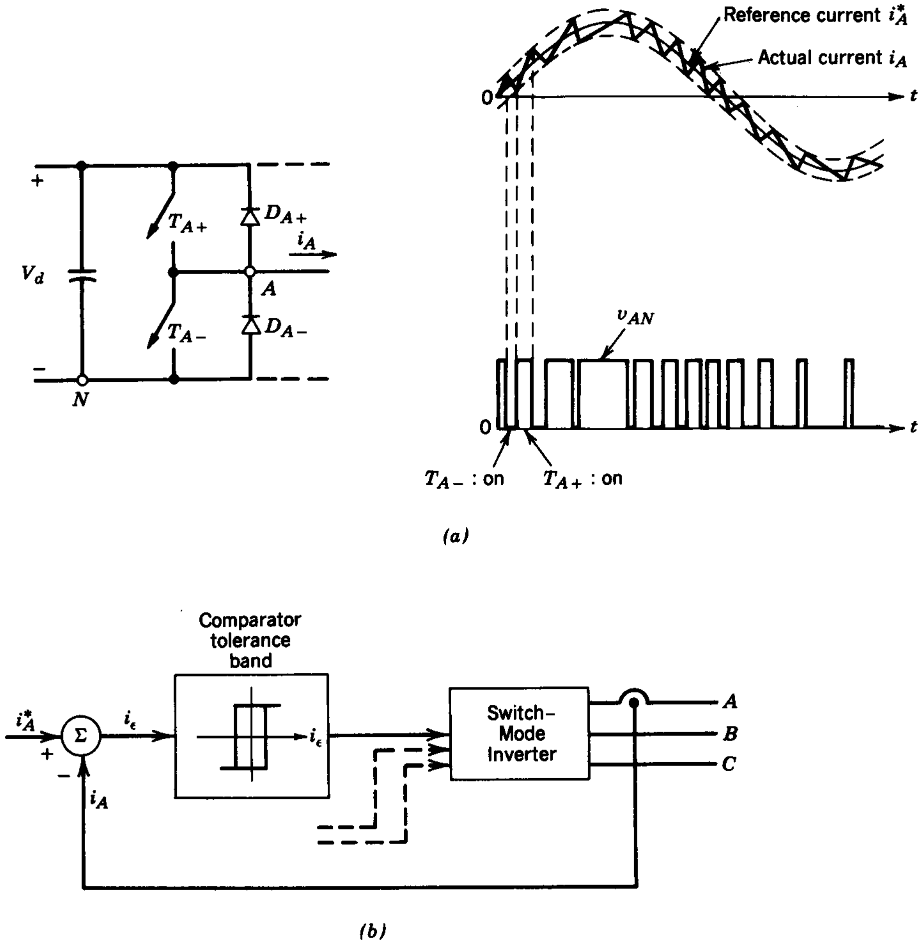

Figure 8-35 Tolerance band current control.

- Results in a variable frequency operation

Fixed-Frequency Operation

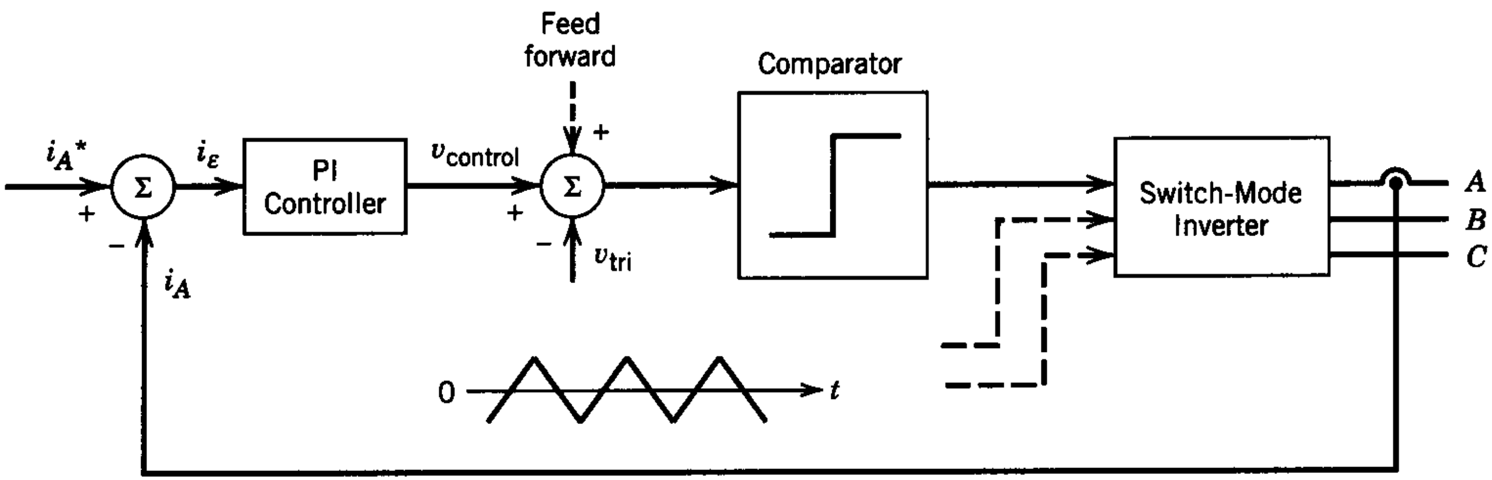

Figure 8-36 Fixed-frequency current control.

- Better control is possible using *dq* analysis

Transition from Inverter to Rectifier Mode

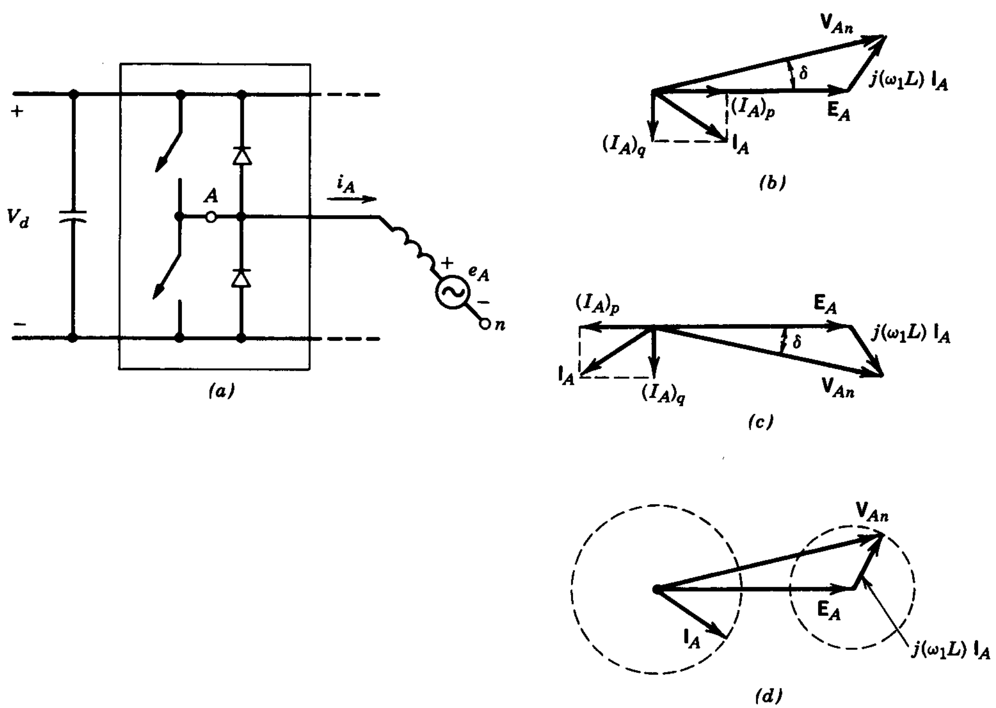

Figure 8-37 Operation modes: (*a*) circuit; (*b*) inverter mode; (*c*) rectifier mode; (*d*) constant I_A.

- Can analyze based on the fundamental-frequency components

Summary of DC-AC Inverters

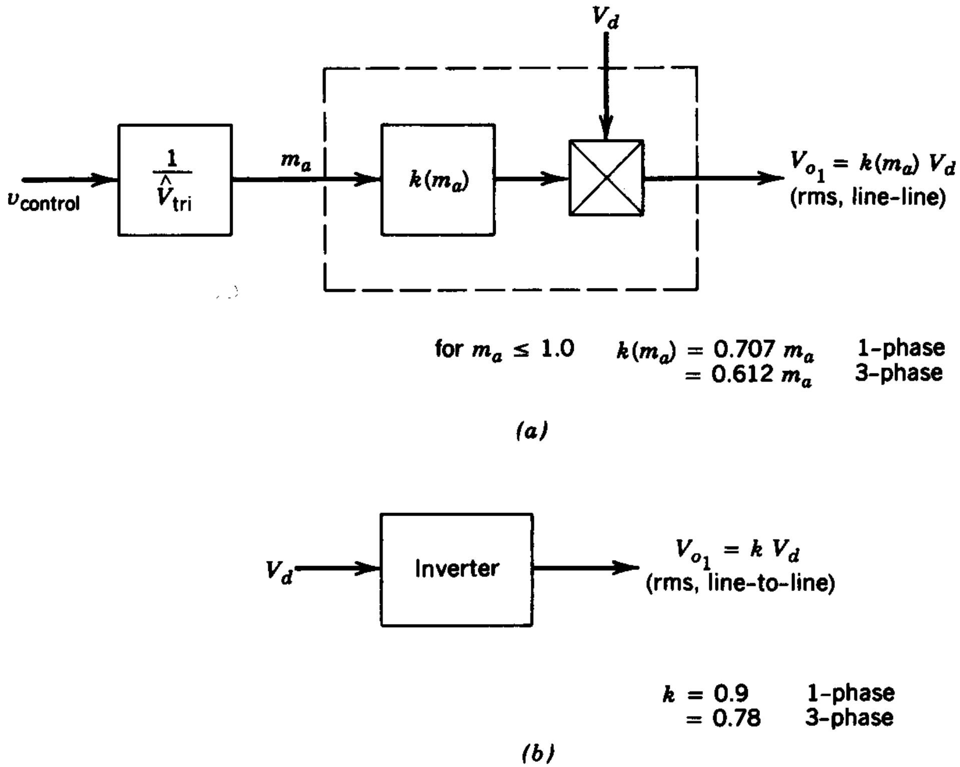

Figure 8-38 Summary of inverter output voltages: (a) PWM operation ($m_a \leq 1$); (b) square-wave operation.

- Functional representation in a block-diagram form