ELGC06

Pulse Width Modulation Techniques for Voltage-Fed Inverters

PWM Principle

The dc input to the inverter is "chopped" by switching devices in the inverter. The amplitude and harmonic content of the ac waveform is controlled by the duty cycle of the switches. The fundamental voltage v_1 has max. amplitude = $4V_d/\pi$ for a square wave output but by creating notches, the amplitude of v_1 is reduced (see next slide).

PWM Principle (cont'd)

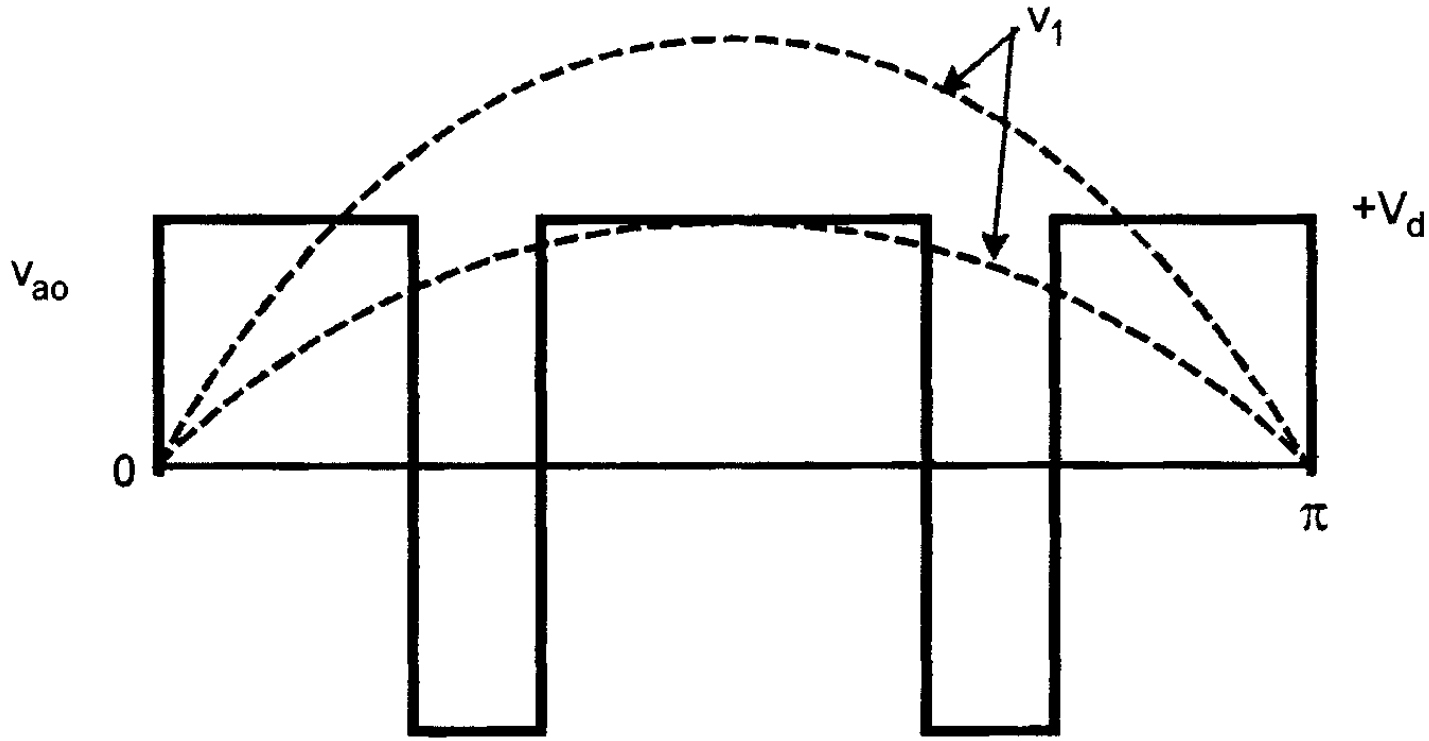


Figure 5.17 PWM principle to control output voltage

PWM Techniques

Various PWM techniques, include:

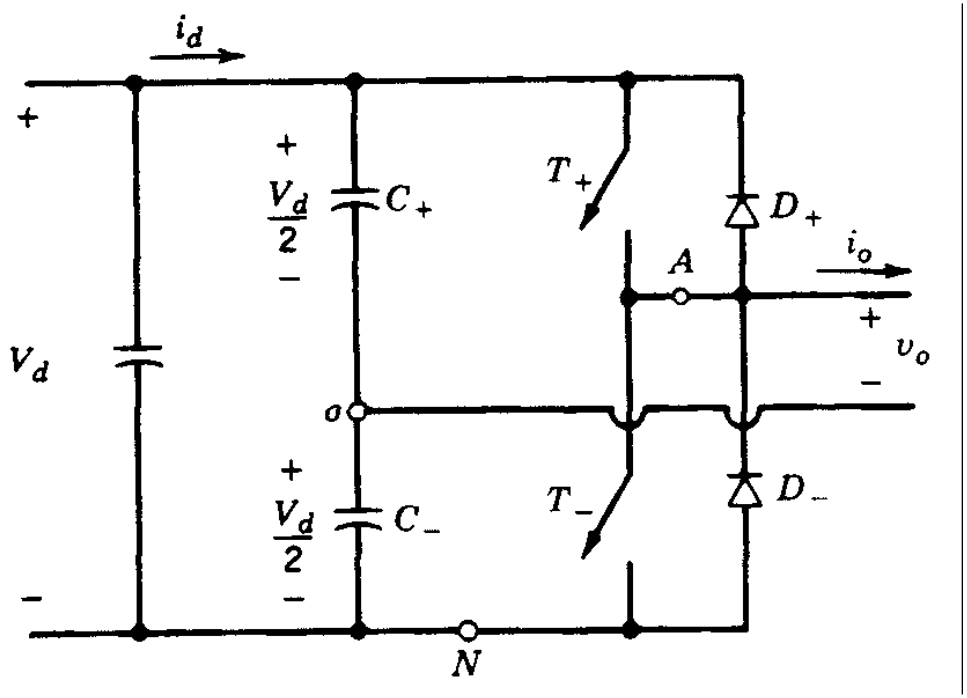
- Sinusoidal PWM (most common)
- Selected Harmonic Elimination (SHE) PWM
- Space-Vector PWM
- Instantaneous current control PWM
- Hysteresis band current control PWM
- Sigma-delta modulation

Sinusoidal PWM

The most common PWM approach is sinusoidal PWM. In this method a triangular wave is compared to a sinusoidal wave of the desired frequency and the relative levels of the two waves is used to control the switching of devices in each phase leg of the inverter.

Sinusoidal PWM (cont'd)

Single-Phase (Half-Bridge) Inverter Implementation



Sinusoidal PWM (cont'd)

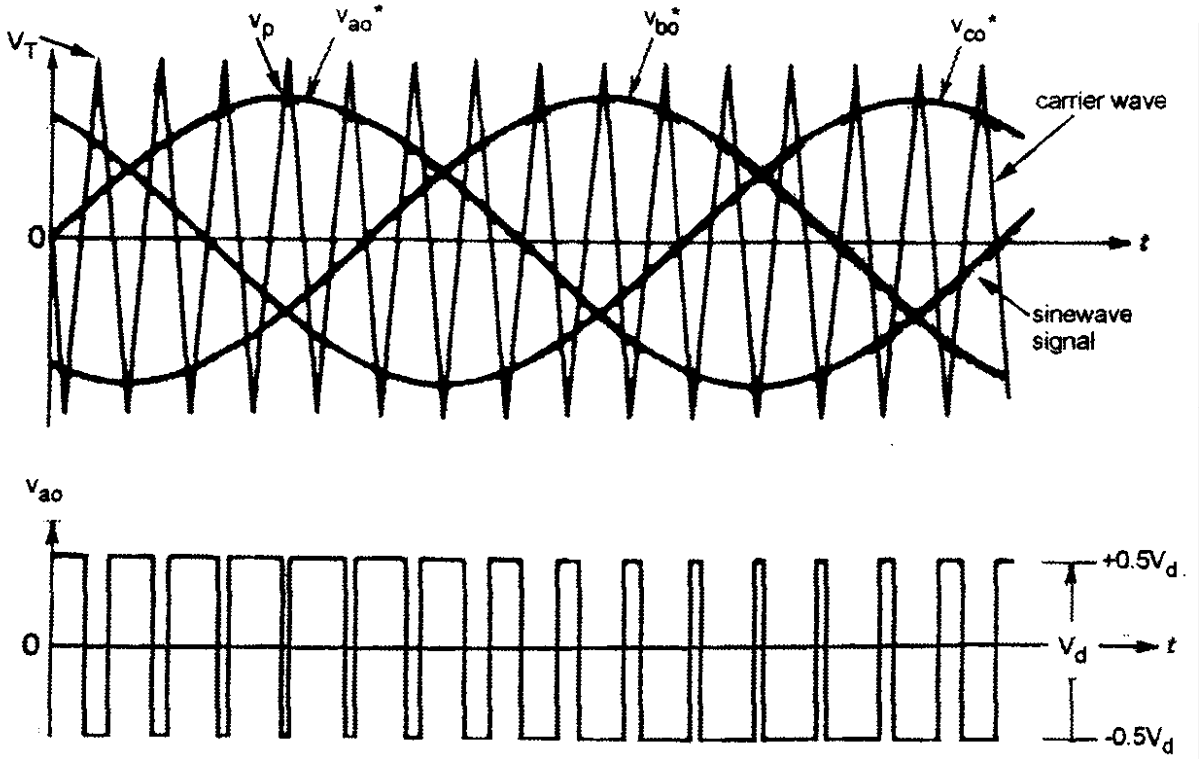


Figure 5.18 Principle of sinusoidal PWM for three-phase bridge inverter

when $v_{a0} > v_T$ T_+ on; T_- off; $v_{a0} = \frac{1}{2}V_d$

$v_{a0} < v_T$ T_- on; T_+ off; $v_{a0} = -\frac{1}{2}V_d$

Sinusoidal PWM (cont'd)

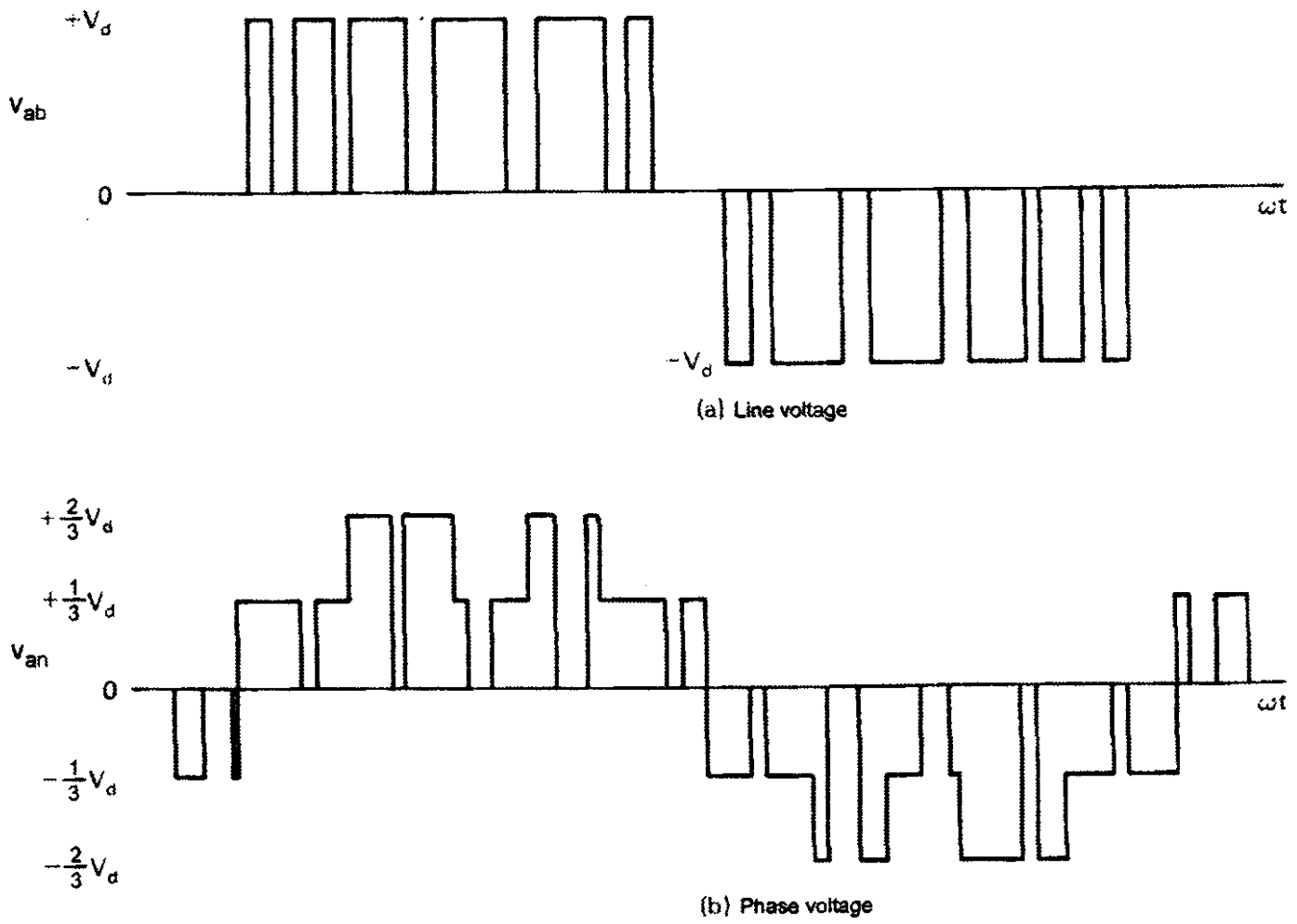


Figure 5.19 Line and phase voltage waves of PWM inverter

Sinusoidal PWM (cont'd)

Definition of terms:

Triangle waveform switching freq. = f_c (also called carrier freq.)

Control signal freq. = f (also called modulation freq.)

Amplitude modulation ratio, $m = \frac{V_p}{V_T}$

Peak amplitude of control signal

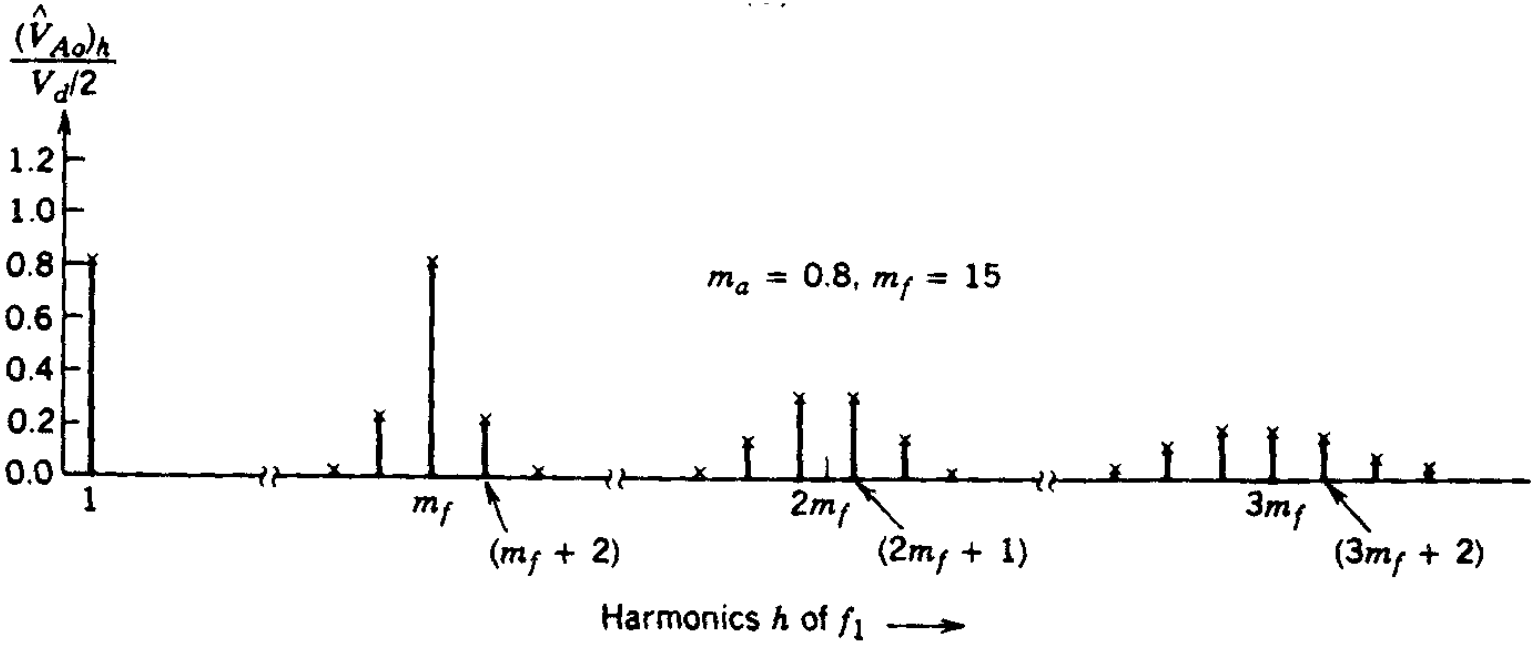
Peak amplitude of triangle wave

Frequency modulation ratio,

$$m_f(P) = f_c / f$$

Sinusoidal PWM (cont'd)

Harmonics



Note: Nearly independent of m_f (P) for $m_f \geq 9$.

Sinusoidal PWM (cont'd)

Harmonics (cont'd)

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.

Sinusoidal PWM (cont'd)

- At high f_c the nominal leakage inductance of the machine will effectively filter out the inverter line current harmonics at high switching frequencies. High f_c leads to higher switch losses but lower machine harmonic loss.
- Choose m_f (P) = odd integer ∴ it eliminates even harmonics.

Sinusoidal PWM (cont'd)

- At m=1, the max. value of fundamental peak voltage $=0.5V_d = 0.7855 \cdot V_{pk}^{sq.wave}$ $(=4V_d/2\pi)$. This max. value can be increased to $0.907V_{pk}^{sq.wave}$ by injecting 3rd order harmonics - this is a common mode voltage and does not affect torque production.

Sinusoidal PWM (cont'd)

Overmodulation (m > 1.0)

Gives non-linear control and increases harmonics but results in greater output.

$$\frac{V_d}{2} < (\widehat{V_{A0}})_1 < \frac{4}{\pi}\frac{V_d}{2} \quad \text{for } m > 1.$$

(see text)

Sinusoidal PWM (cont'd)

Two regions of operation - constant torque and constant power.

For constant power, max. voltage obtained by operating inverter in square wave mode.

For constant torque, voltage can be controlled by PWM principle.

Sinusoidal PWM (cont'd)

Frequency Relation

It is desirable to have $m_f(P)$ = integer. However, as fundamental freq. decreases, f_c would also have to decrease - not desirable in terms of machine harmonic loss. An optimal choice of f_c for different f's is shown below.

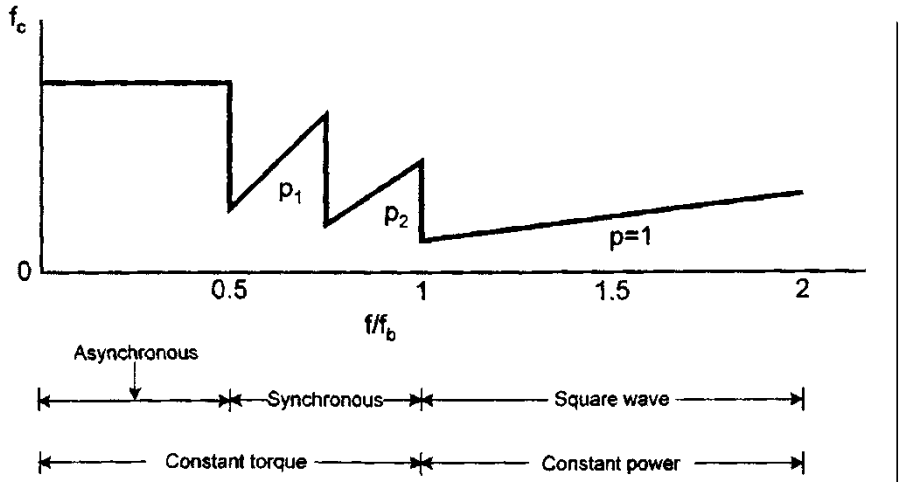
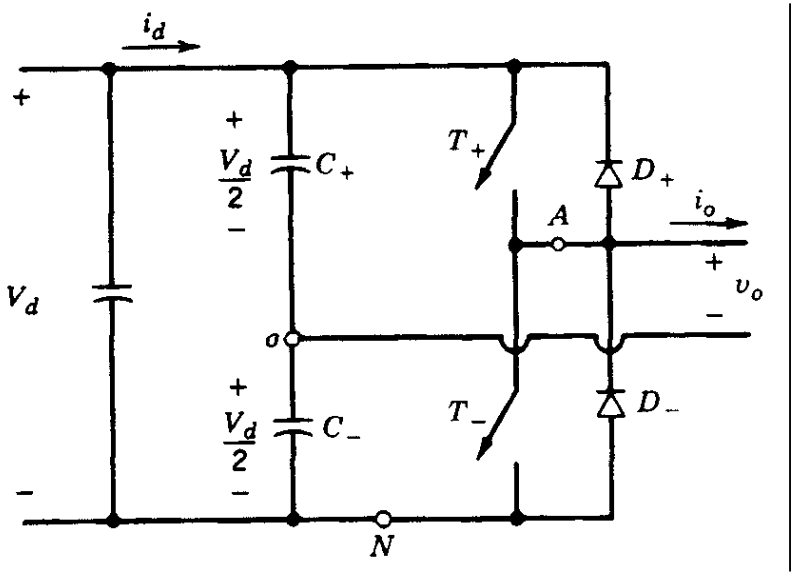


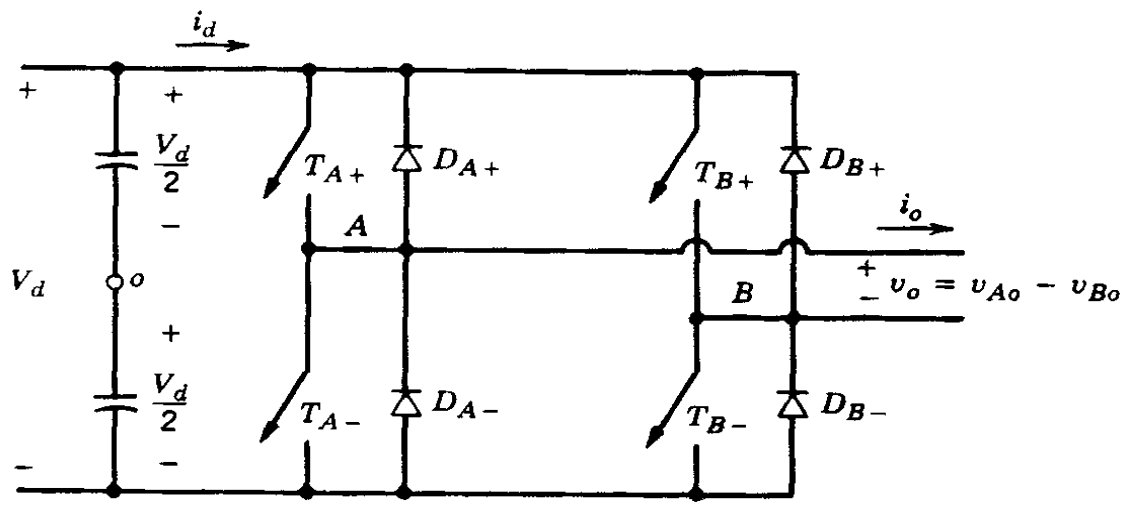
Figure 5.22 Relation of carrier frequency with (f/f_b) ratio

Single Phase Half-Bridge Inverter



- C_+ , C_- large and equal => voltage divides exactly between capacitors at all times.
- The current i_0 must flow through parallel combination of C_+ and C_- => i_0 has no dc component in steady state.

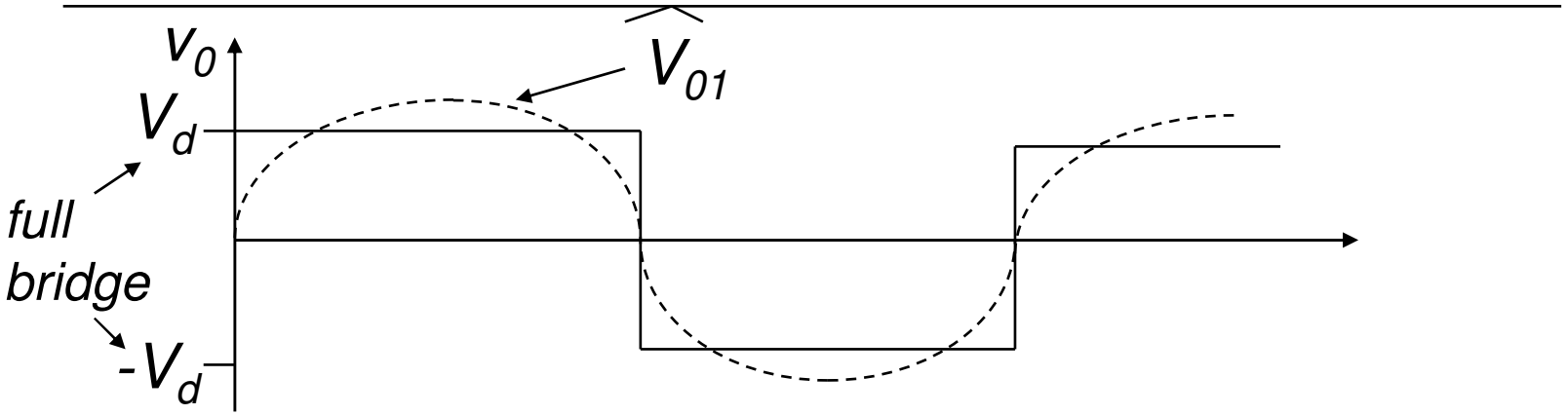
Single Phase Full-Bridge Inverter



Essentially two one-leg inverters with the same dc input voltage.

Max. output voltage = 2 x max. output voltage of ½-bridge. => output current is half (useful at high powers since it means less paralleling of devices.)

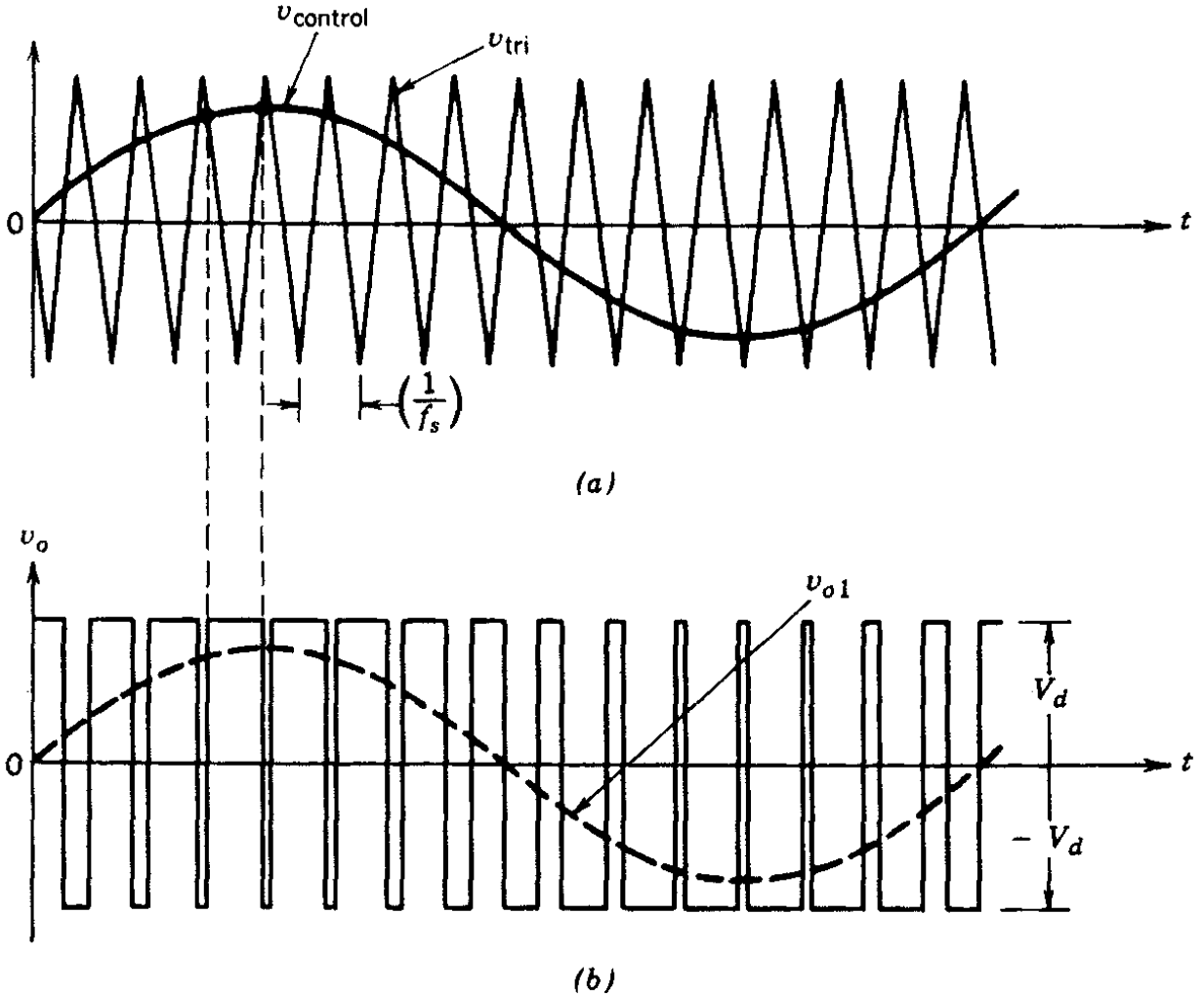
Square Wave Inverter



$$\hat{V}_{01} = \frac{4}{\pi} V_d$$

No pulse width control . Frequency control is possible. Amplitude control is possible if V_d is varied.

Bipolar PWM Switching



Bipolar PWM Switching (cont'd)

Switch pairs: (T_{A+}, T_{B-}) and (T_{B+}, T_{A-})

Output of leg B is negative of leg A

output => $v_{B0}(t) = -v_{A0}(t) => v_0(t) = 2v_{A0}(t)$

$\therefore$ Peak of fundamental frequency component, $\hat{V}_{01} = m_a V_d \quad (m_a \leq 1.0)$

$$V_d < \hat{V}_{01} < \frac{4}{\pi} V_d \quad (m_a > 1.0)$$

Dead Time Effect

Because of finite turn-on time and turn-off time of switches, you wait a blanking time, t_d after switching one switch off in a leg before switching on the other switch in the same leg. The blanking time will increase or decrease the output slightly depending on the direction of the load current.

Also, additional high frequencies appear in the output waveform.

Dead Time Effect (cont'd)

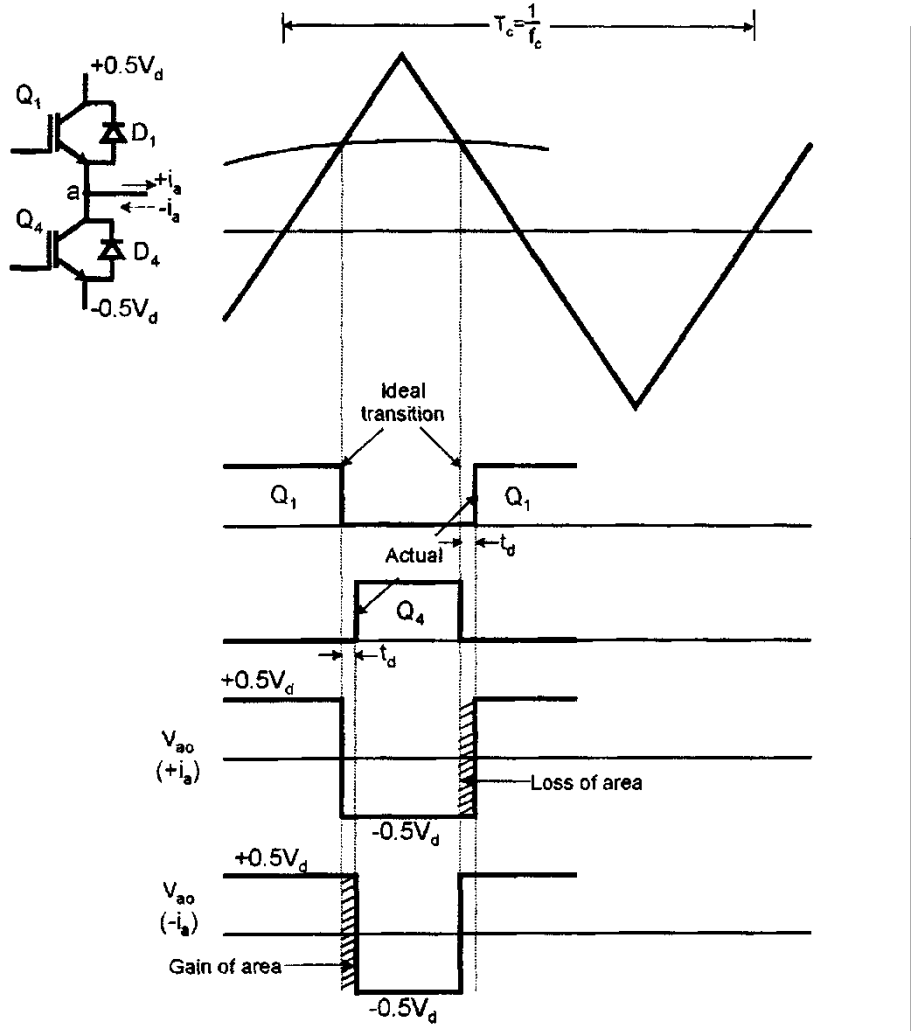
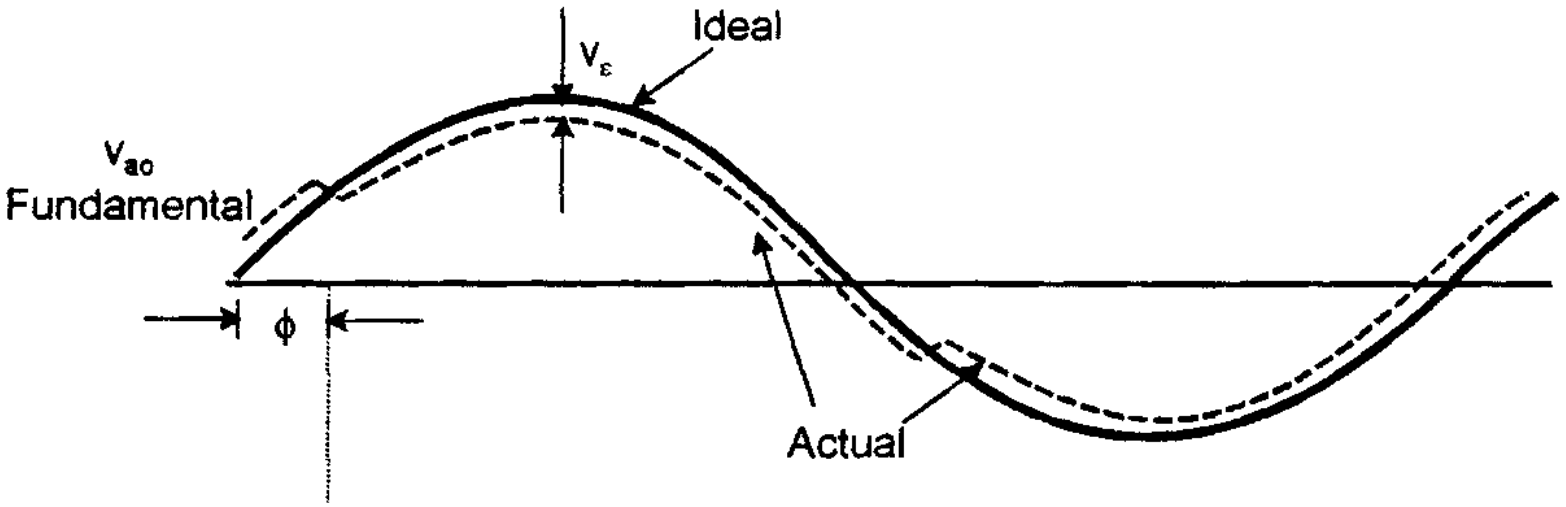


Figure 5.23 Waveforms of half-bridge inverter explaining dead-time effect

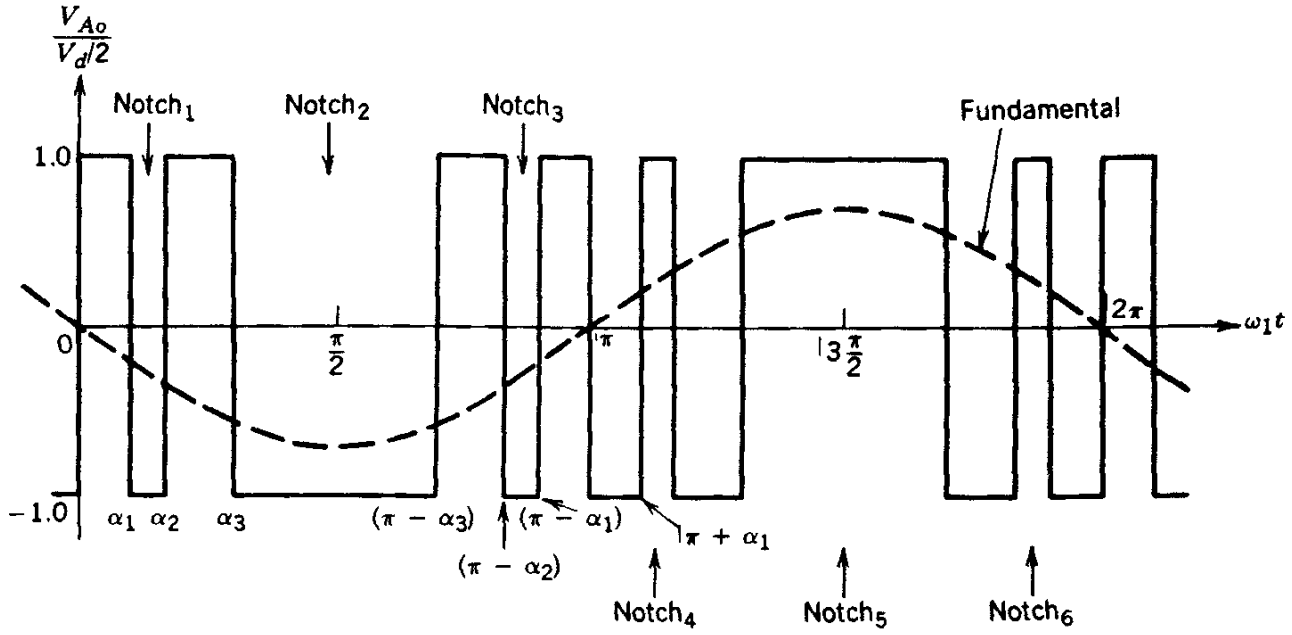
Dead Time Effect (cont'd)



Current or voltage feedback compensation can be used to minimize waveform distortion due to the dead time effect.

Selective Harmonic Elimination

By placing notches in the output waveform at proper locations, certain harmonics can be eliminated. This allows lower switching frequencies to be used -> lower losses, higher efficiency.



Selective Harmonic Elimination (cont'd)

General Fourier series of wave is given by:

$$v(t) = \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t)$$

where $$a_n = \frac{1}{\pi} \int_0^{2\pi} v(t) \cos(n\omega t) d(\omega t)$$

and $$b_n = \frac{1}{\pi} \int_0^{2\pi} v(t) \sin(n\omega t) d(\omega t)$$

Selective Harmonic Elimination (cont'd)

For a waveform with quarter-cycle symmetry, only the odd harmonics with sine components will appear, i.e. $a_n=0$ and

$$v(t) = \sum_{n=1}^{\infty} b_n \sin n\omega t$$

where $$b_n = \frac{4}{\pi} \int_0^{2\pi} v(t) \sin(n\omega t) d(\omega t)$$

Selective Harmonic Elimination (cont'd)

It can be shown (see text for derivation) that

$$b_n = \frac{4}{n\pi}\left[1 + 2\sum_{K=1}^{K}(-1)^K \cos n\alpha_K\right]$$

Thus we have K variables (i.e. α_1, α_2, α_3, ... α_K) and we need K simultaneous equations to solve for their values.With K α angles, K-1 harmonics can be eliminated.

Selective Harmonic Elimination (cont'd)

Consider the 5th and 7th harmonics (the 3rd order harmonics can be ignored if the machine has an isolated neutral). Thus K=3 and the equations can be written as:

Fundamental:

$$b_1 = \frac{4}{\pi}(1 - 2\cos\alpha_1 + 2\cos\alpha_2 - 2\cos\alpha_3)$$

5th Harmonic:

$$b_5 = \frac{4}{5\pi}(1 - 2\cos 5\alpha_1 + 2\cos 5\alpha_2 - 2\cos 5\alpha_3) = 0$$

7th Harmonic:

$$b_7 = \frac{4}{7\pi}(1 - 2\cos 7\alpha_1 + 2\cos 7\alpha_2 - 2\cos 7\alpha_3) = 0$$

Selective Harmonic Elimination (cont'd)

These transcendental equations can be solved numerically for the notch angles α_1, α_2, and α_3 for a specified fundamental amplitude. For example, if the fundamental voltage is 50% (i.e. $b_1=0.5$) the α values are:

$$\alpha_1=20.9^\circ,\ \alpha_2=35.8^\circ,\ \text{and}\ \alpha_3=51.2^\circ$$

This approach can easily be implemented in a microcomputer using a lookup table for notch angles (see text).

Selective Harmonic Elimination (cont'd)

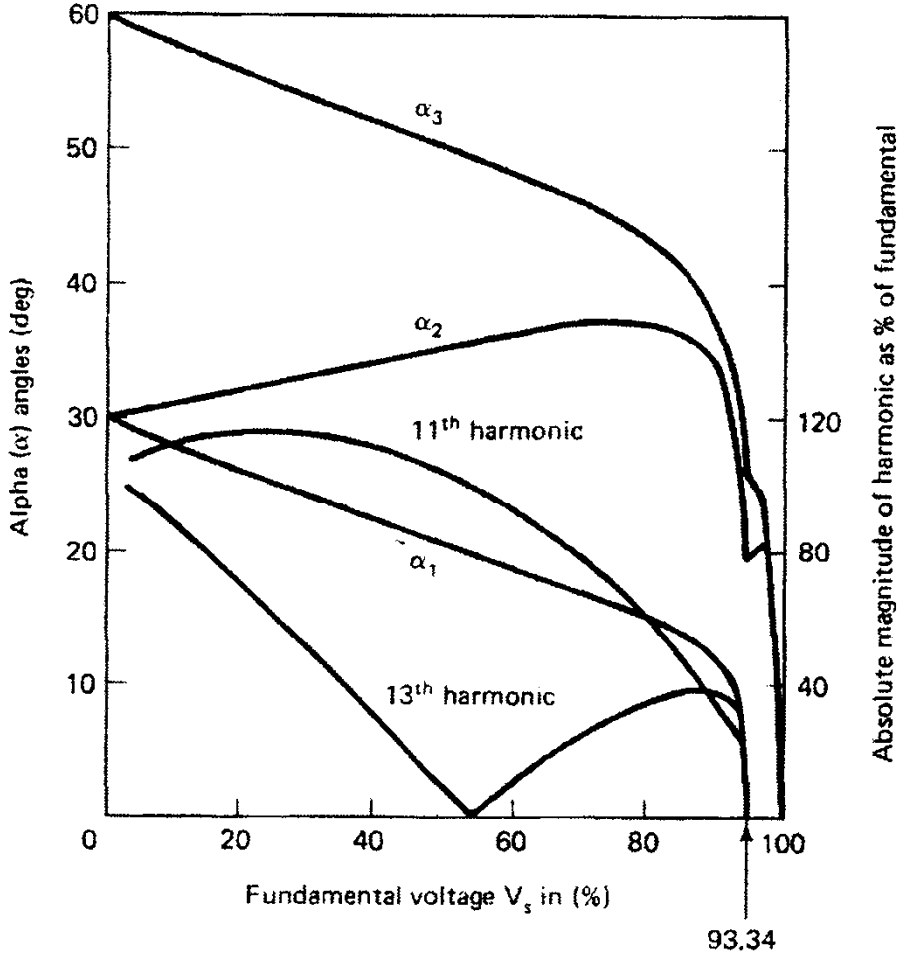


Figure 5.26 Notch angle relation with fundamental output voltage for 5th and 7th harmonic eliminatior

Current Regulated PWM

The flux and torque output of an ac motor is directly controlled by the current input to the motor. Thus having current control on the output of a voltage-fed converter with voltage control PWM is important. A feedback current loop is used to control the machine current.

Two PWM techniques for current control will be considered:

1. Instantaneous Current Control
2. Hysteresis Band Current Control

Instantaneous Current Control

The below figure shows an instantaneous current control scheme with sinusoidal PWM in the inner control loop.

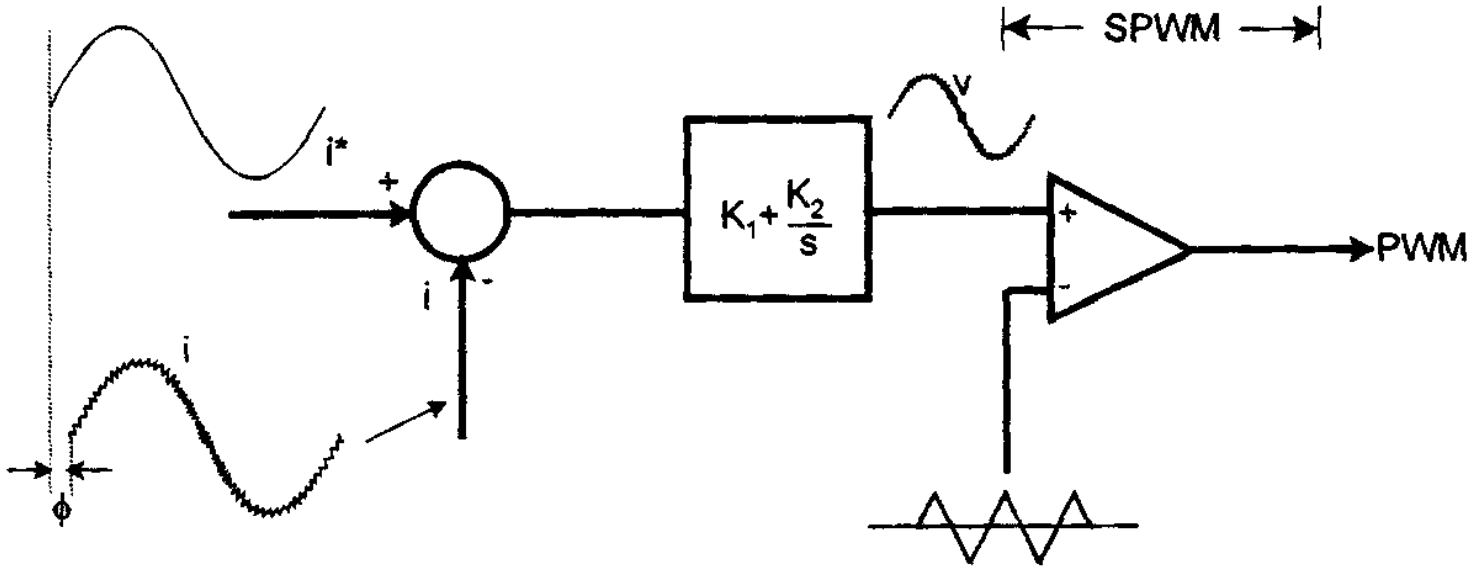


Figure 5.37 Control block diagram for instantaneous current control SPWM

Instantaneous Current Control (cont'd)

Actual current i is compared to commanded current i^* and the error fed to a proportional-integral (P-I) controller. The rest of the circuit is the standard PWM topology. For a 3Φ inverter, three such controllers are used.

Although the control approach is simple, this method produces significant phase lag at high frequencies which are very harmful to high-performance drives.

Hysteresis-Band Current Control

In hysteresis-band current control the actual current tracks the command current within a hysteresis band.

In this approach a sine reference current wave is compared to the actual phase current wave. As the current exceeds a prescribed hysteresis band, the upper switch in the half-bridge is turned off and the lower switch is turned on. As the current goes below the hysteresis band, the opposite switching takes place.

Hysteresis-Band Control (cont'd)

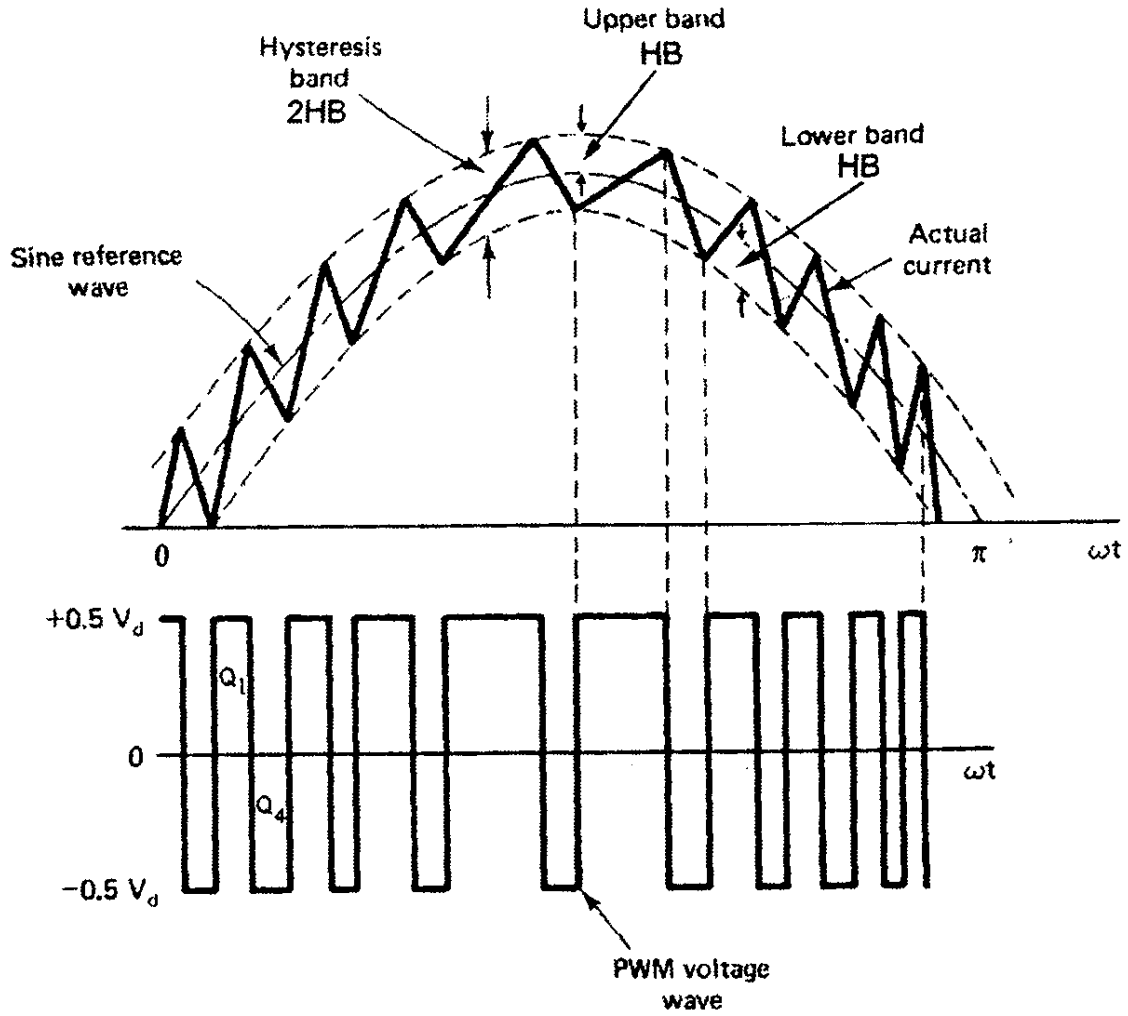


Figure 5.38 Principle of hysteresis-band current control

Hysteresis-Band Control (cont'd)

With upper switch closed, the positive current slope is given by:

$$\frac{di}{dt} = \frac{0.5V_d - V_{cm}\sin\omega_e t}{L}$$

where $0.5V_d$ is the applied dc voltage,

$V_{cm}\sin\omega_e t$ is the opposing load counter EMF, and L = effective load inductance.

Similarly, with the lower switch closed, the negative current slope is given by:

$$\frac{di}{dt} = \frac{-(0.5V_d - V_{cm}\sin\omega_e t)}{L}$$

Hysteresis-Band Control (cont'd)

Pk-to-pk current ripple and switching freq. are related to width of hysteresis band. Select width of hysteresis band to optimally balance harmonic ripple and inverter switching loss.

Current control tracking is easy at low speed but at high speeds, when counter EMF is high, current tracking can be more difficult.

Hysteresis-Band Control (cont'd)

A simple control block diagram for implementing hysteresis band PWM is shown below:

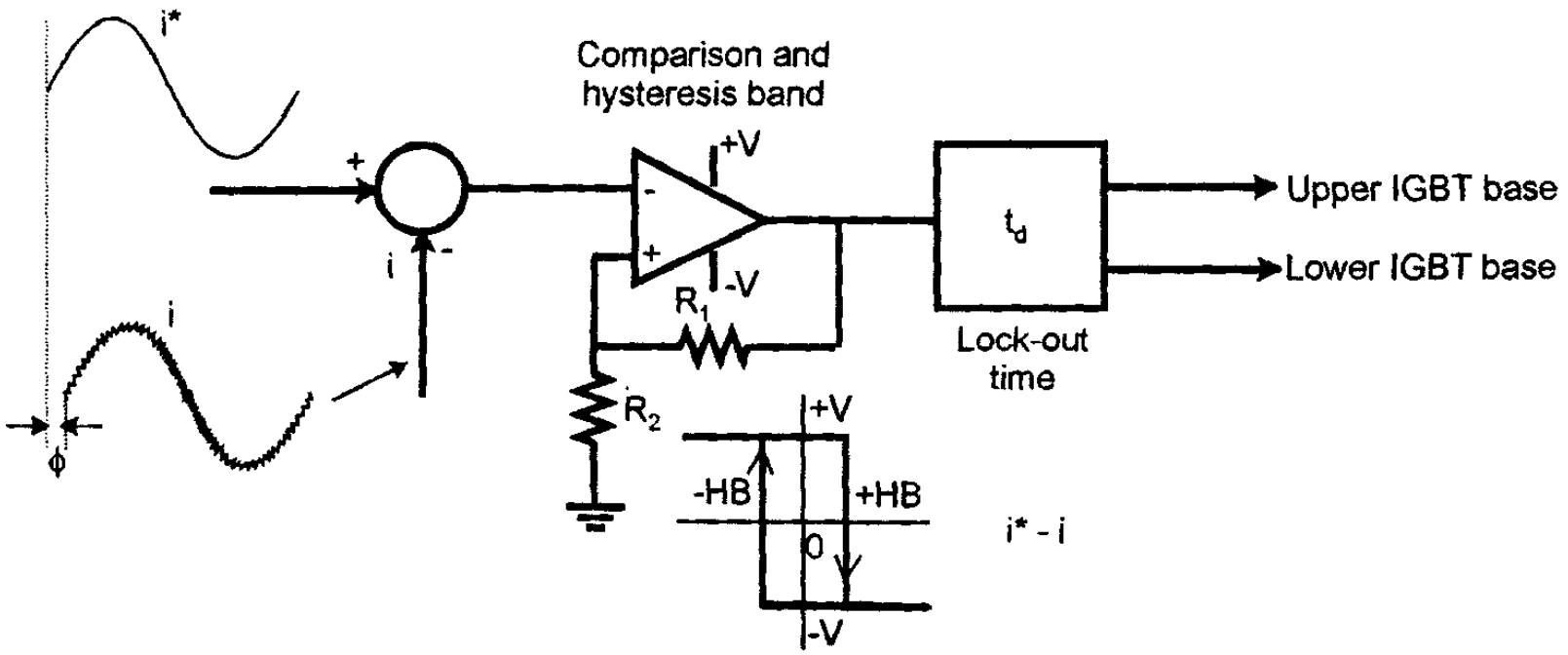


Figure 5.39 Control block diagram for hysteresis-band PWM

Hysteresis-Band Control (cont'd)

The error in the control loop is input to a Schmitt trigger ckt. The width of the hysteresis band HB is given by:

$$HB = V \frac{R_2}{R_1 + R_2}$$

Upper switch on: $(i^*-i) > HB$

Lower switch on: $(i^*-i) < -HB$

One control ckt used per phase.

Hysteresis-Band Control (cont'd)

This approach is very popular because of simple implementation, fast transient response, direct limiting of device pk. current, and practical insensitivity to dc link voltage ripple (=> small filter capacitor).

However, PWM freq. is not const. which leads to non-optimal harmonic ripple in machine current. Can be overcome by adaptive hysteresis band. Also, significant phase lag at high freqs. is a drawback of this method for high-performance drives.

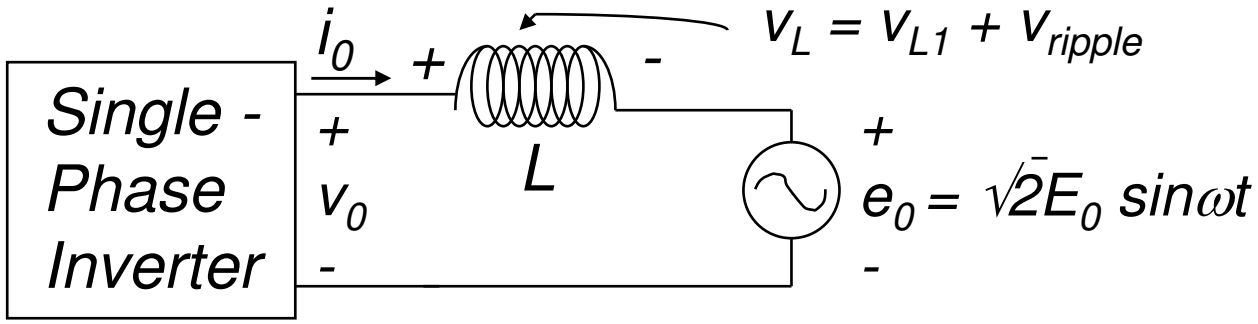
Sigma Delta Modulation

Sigma-delta modulation is a useful technique for high frequency link converter systems - uses integral half-cycle pulses to generate variable freq., variable voltage sinusoidal waves.

Output Ripple

The output ripple may be defined as the difference between the instantaneous value of the current/voltage compared to the value of the fundamental frequency component.

Consider the load to be an ac motor.



$$v_0 = v_{01} + v_{ripple} \; ; \; i_0 = i_{01} + i_{ripple}$$

Output Ripple (cont'd)

Using superposition:

$$v_{ripple}(t) = v_0(t) - v_{01}(t)$$

$$i_{ripple}(t) = \frac{1}{L}\int_0^t v_{ripple}(\xi)d\xi + k$$

k: *constant*

Note: The ripple is independent of the power being transferred to the load.