Inverters 2
Pulse Width Modulation

Basic Voltage Source Inverters (Summary)

- Single and three phase outputs may be produced using inverter circuits.

- Simple modulation techniques using fundamental frequency switching can produce a basic AC waveform.

- The output voltage of the inverter contains harmonics components as well as the desired fundamental frequency, These give rise harmonic currents leading to excess heating and vibration.

- Harmonic currents may be limited by inductive loads or passive power filters.

- Fundamental frequency switching gives rise to low order harmonics which are hard to filter from the fundamental.

Better Quality AC output

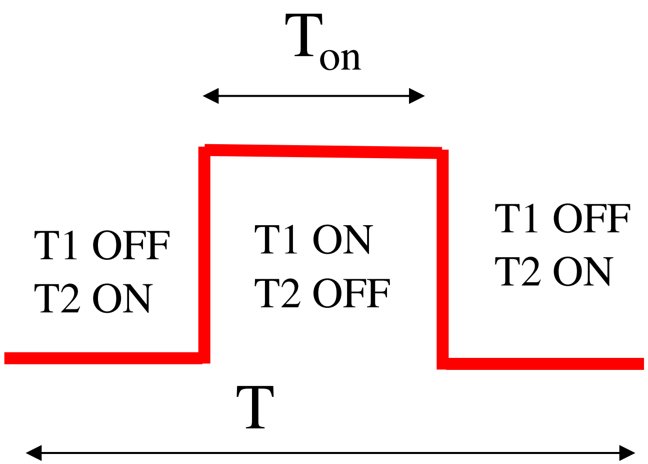
How do we obtain a better quality AC waveform?

NOTE:

- Normally it is the load current NOT the applied voltage. that is important.
- For Inductive loads impedance increases with frequency. High frequency voltage harmonics will give rise to lower load current than low order harmonics of equal magnitude.

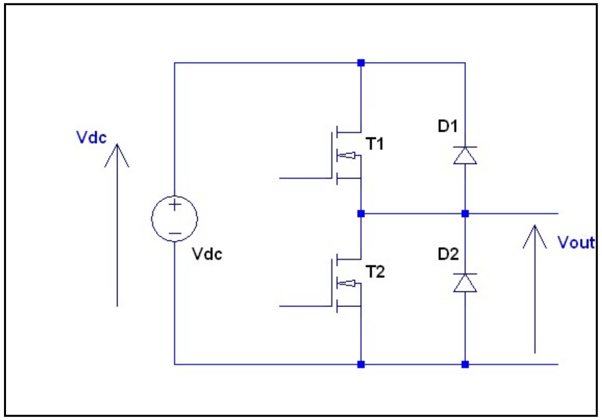
Can we increase the frequency of the switching harmonics whilst still producing the required fundamental ?

Pulse Width Modulation



$$\overline{V}_{out}(t) = V_{dc}\frac{T_{on}(t)}{T_s}$$

We have previously used pulse width control to vary a DC output voltage.



If the on time is made time variant then the average voltage in each switching period (T_s) also becomes time variant.
The ratio $T_{on}(t)/Ts$ is defined as the instantaneous modulation index m(t)

Average Output Voltage

A single inverter leg produces an average output voltage:

$$V_{out} = V_{dc} \frac{T_{on}}{T_s}$$

Define a *duty cycle* or *modulation index*

$$m = \frac{T_{on}}{T_s}$$

Hence

$$\boxed{V_{out} = mV_{dc}}$$

m must be between 0 and 1.

We can make *m(t)* vary in time therefore we can produce **any voltage and any frequency we desire (within the bounds fixed by the switching frequency and *Vdc*).**

Sinusoidal PWM

By varying the modulation index the instantaneous average voltage in any time interval T can controlled.

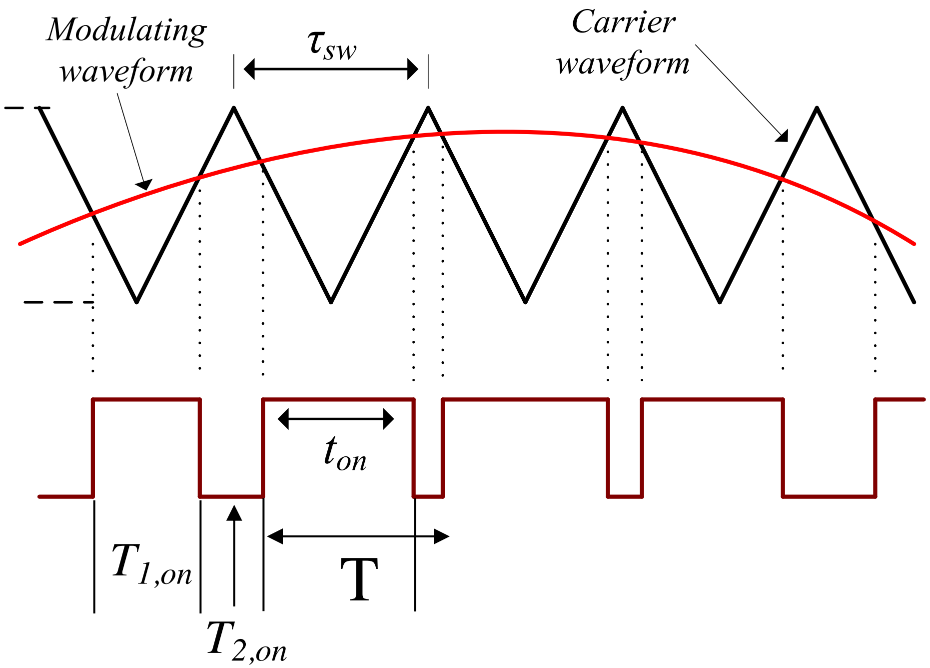
By controlling this instantaneous average to track a sinusoidal reference it is possible generate an AC (Fundamental) voltage at the bridge-leg output.

$$m_a(t) = 0.5 + \frac{M}{2} \cdot Sin\,(\omega t)$$

$$0 \leq M \leq 1$$

By controlling M and ω the magnitude and frequency of the fundamental ac output can be controlled.

Pulse-width Modulation

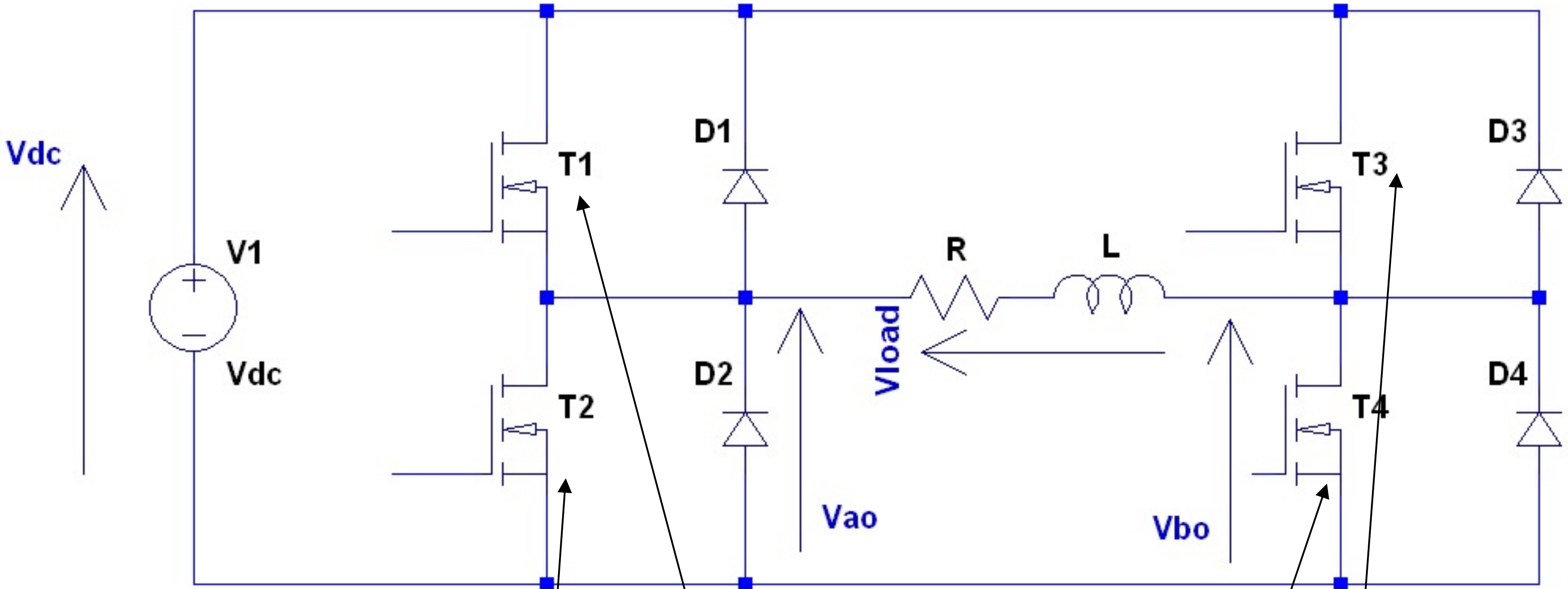


$$f_{sw} = \frac{1}{\tau_{sw}} = \frac{1}{T_s}$$

$$m = \frac{t_{on}}{T_s}$$

The sinusoidal modulation waveform is compared with a triangular 'carrier' at the required switching frequency. The upper switch of the bridge-leg is turned ON when the reference exceed the carrier.

Single-phase (H-bridge) PWM



Side b
Switch 1a top
Switch 2a lower

Side b
Switch 1b top
Switch 2b lower

Single Phase Output

- For the single phase H-Bridge it is possible combine the control of the two bridge legs to produce a PWM output using only $+V_{dc}$ and $–V_{dc}$ levels.

- Alternatively the two bridge legs can be controlled independently. This may give an output which includes $+V_{dc}$, 0, and $-V_{dc}$

Single phase sinusoidal PWM

Complimentary modulation for bridges a, b

$$m_a(t) = 0.5 + \frac{M}{2} \cdot Sin\,(\omega t) \qquad \overline{V}_a(t) = m_a(t) \cdot V_{dc}$$

$$m_b(t) = 0.5 - \frac{M}{2} \cdot Sin\,(\omega t) \qquad \overline{V}_b(t) = m_b(t) \cdot V_{dc}$$

$$0 \le M \le 1$$

$$\overline{V}_{ab} = \overline{V}_a(t) - \overline{V}_b(t) = M \cdot Sin\,(\omega t)$$

Output Voltage, averaged over each period (T)

Basic Single Phase PWM

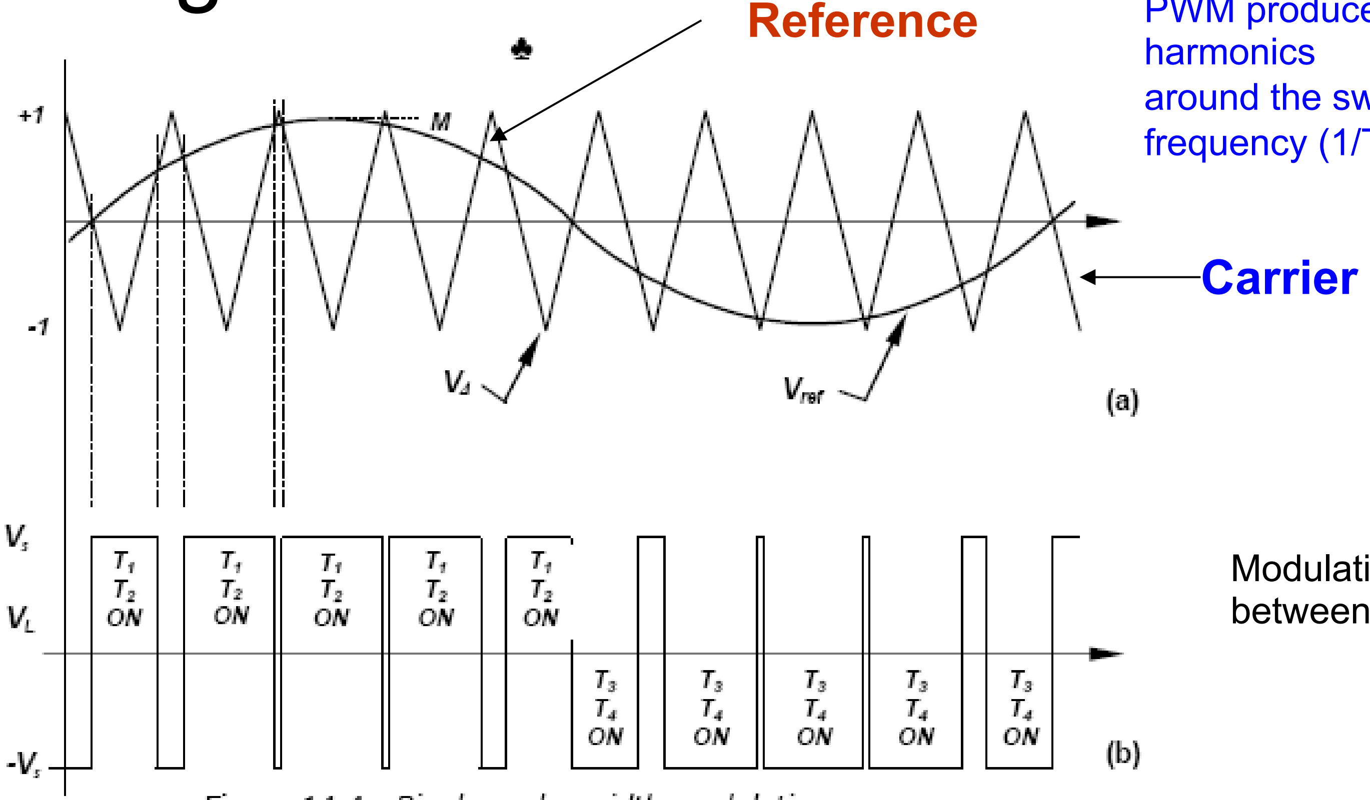


Figure 14.4. *Bipolar pulse width modulation:*
(a) carrier and modulation waveforms and (b) resultant load pwm waveform.

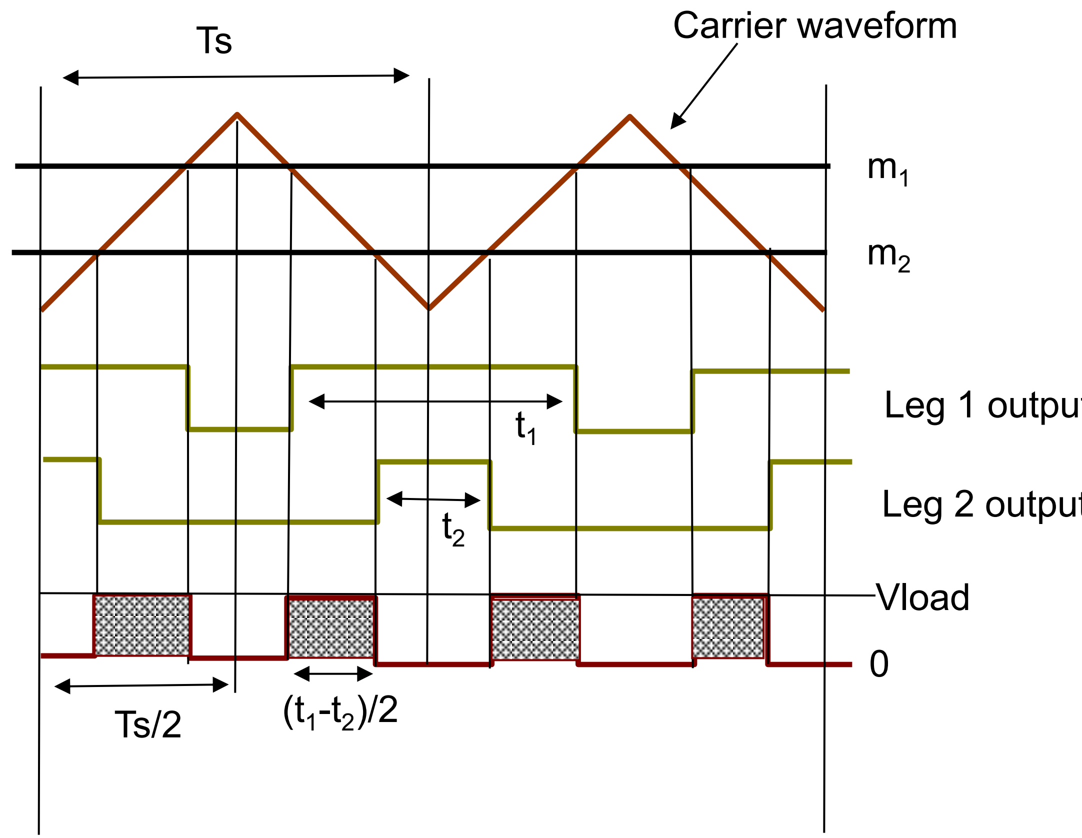
PWM produces harmonics around the switching frequency (1/T)

Modulation between +/-V_{dc}

T1=Switch 1a
T2=Switch 2b
T3=Switch 1b
T4=Switch 2a

PWM Generation (Single Phase)

- Modulation indices of each leg are compared with a triangular carrier waveform.
- Intersects define the turn-on and turn-off instant of each bridge leg.
- With this scheme load sees two output voltage pulses per switching cycle.
- Harmonic spectrum of the applied voltage has components around multiples of the switching frequency.



Single Phase Inverter Output

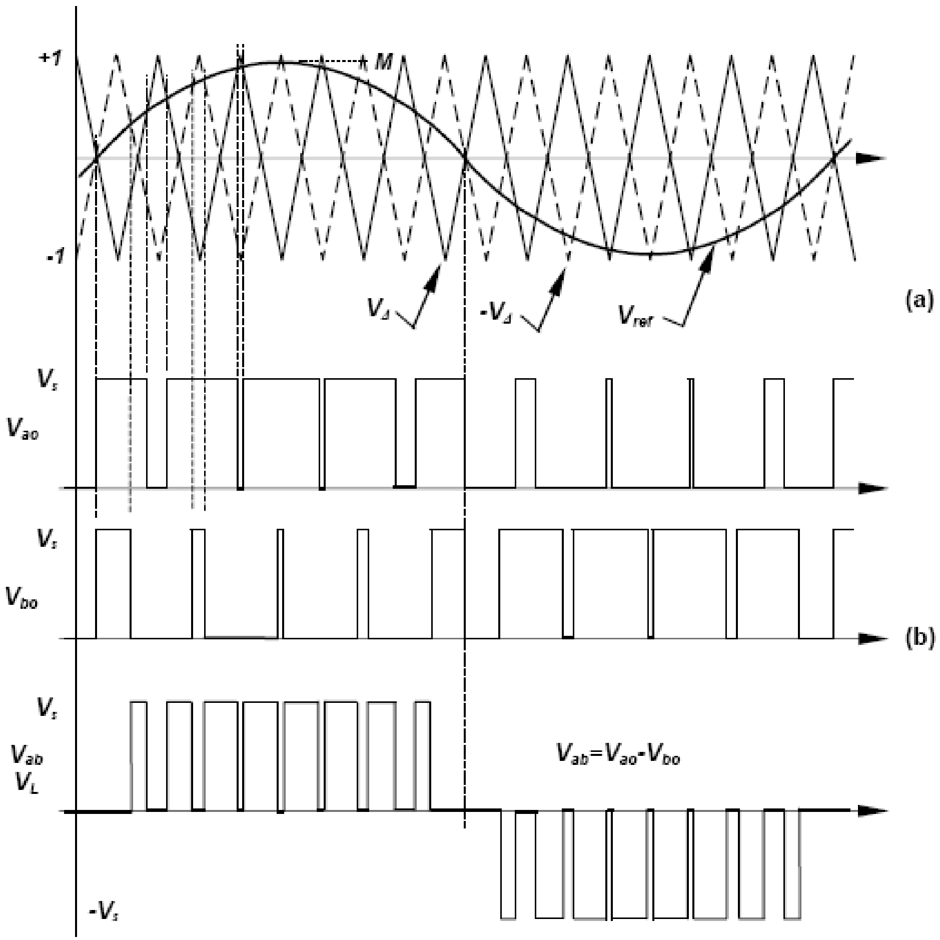


Figure 14.5. *Multilevel (3 level) pulse width modulation: (a) carriers and modulation waveforms and (b) resultant load pwm waveforms.*

Single modulating Waveform and inverted carrier

Bridge leg a and b modulated in anti-phase Results in zero voltage combinations.

Typical Output Spectrum

Recall that output harmonics are attenuated by the load inductance

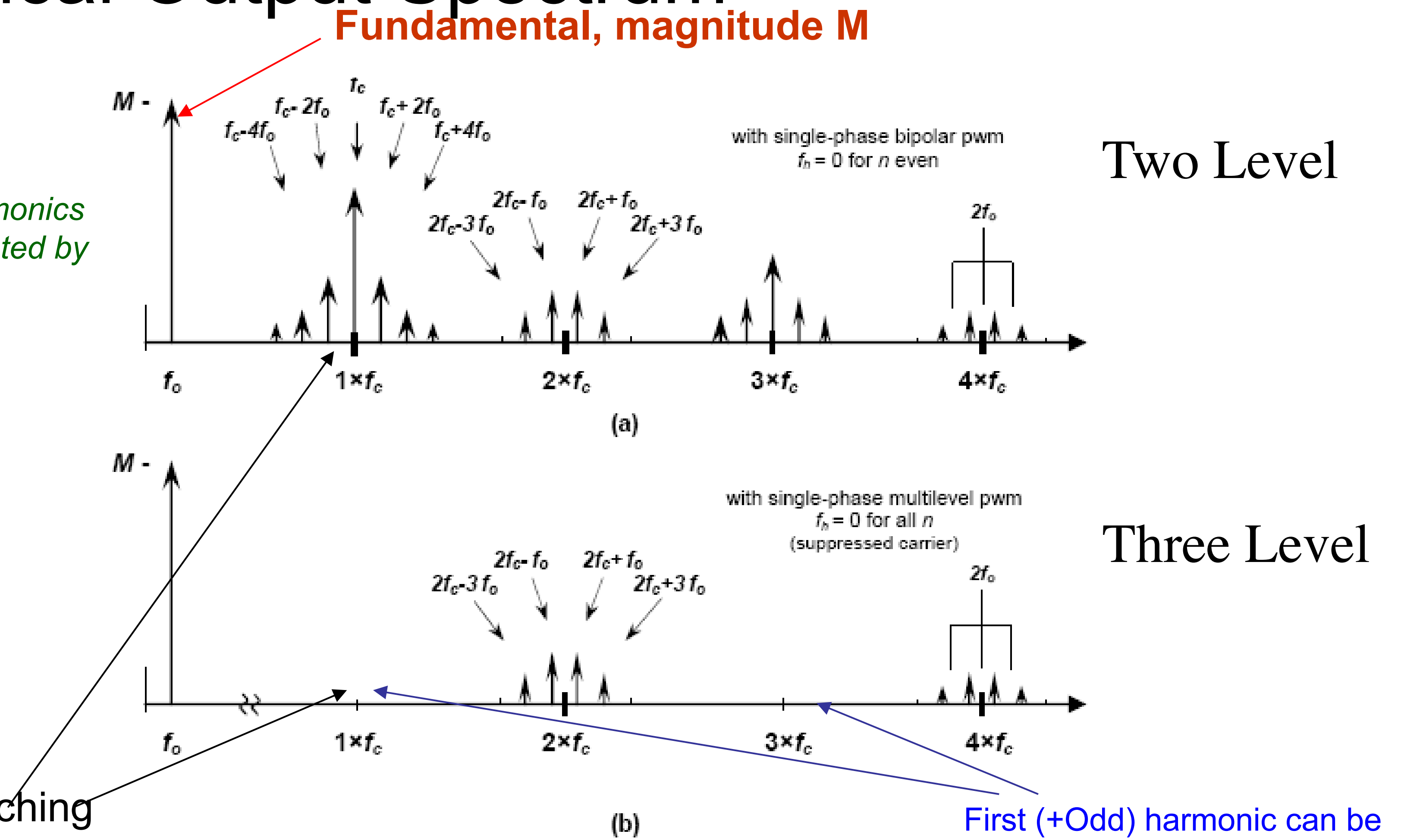


Figure 14.6. *Typical output frequency spectrum for: (a) bipolar pwm and (b) multilevel pwm.*

Switching Frequency

- Switch frequency ($1/T_s$) of the pulse-width modulated (PWM) signal is usually chosen as high as possible to reduce current ripple in the load.
- Max switching frequency is limited by losses and the ability to manage those device losses
- In low power circuits, switching frequency can be as high as ~1 MHz
- High power circuits (say >500kW) may use frequencies of 1kHz or less.

Three Phase PWM

Two Level, three phase, PWM Inverter

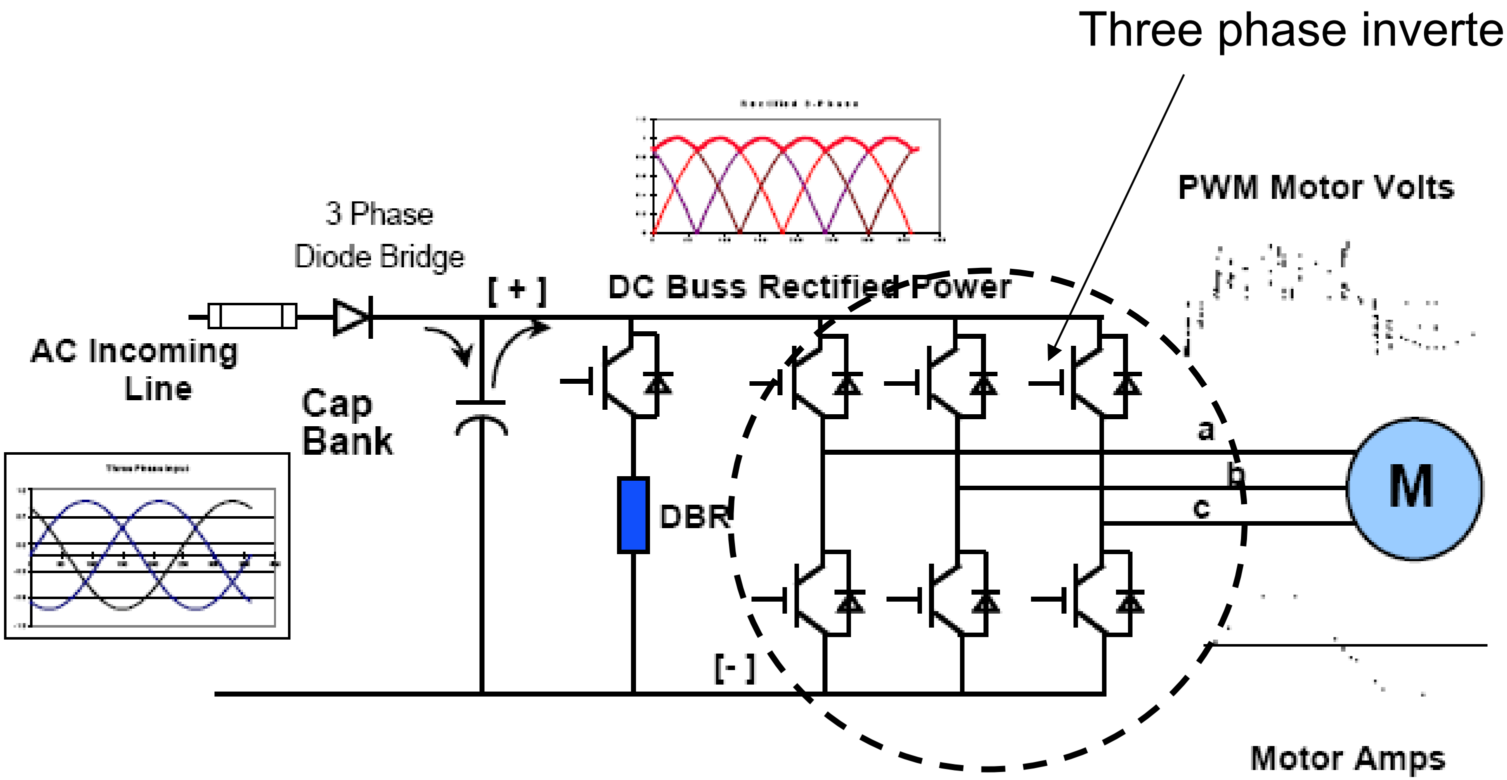


Figure 16. Two-Level PWM IGBT Drive

Source TMGE website

Three phase sinusoidal PWM

$$m_a(t) = 0.5 + \frac{M}{2} \cdot Sin\,(\omega t) \qquad \overline{V}_a(t) = m_a(t) \cdot V_{dc}$$

$$m_b(t) = 0.5 - \frac{M}{2} \cdot Sin\,(\omega t + 120^0) \qquad \overline{V}_b(t) = m_b(t) \cdot V_{dc}$$

$$m_c(t) = 0.5 - \frac{M}{2} \cdot Sin\,(\omega t + 240^0) \qquad \overline{V}_c(t) = m_b(t) \cdot V_{dc}$$

$$0 \le M \le 1$$

$$\overline{V}_{ab} = \overline{V}_a(t) - \overline{V}_b(t) = \frac{\sqrt{3} M V_{dc}}{2} \cdot \sin(\omega t - 30)$$

Three Phase Modulation

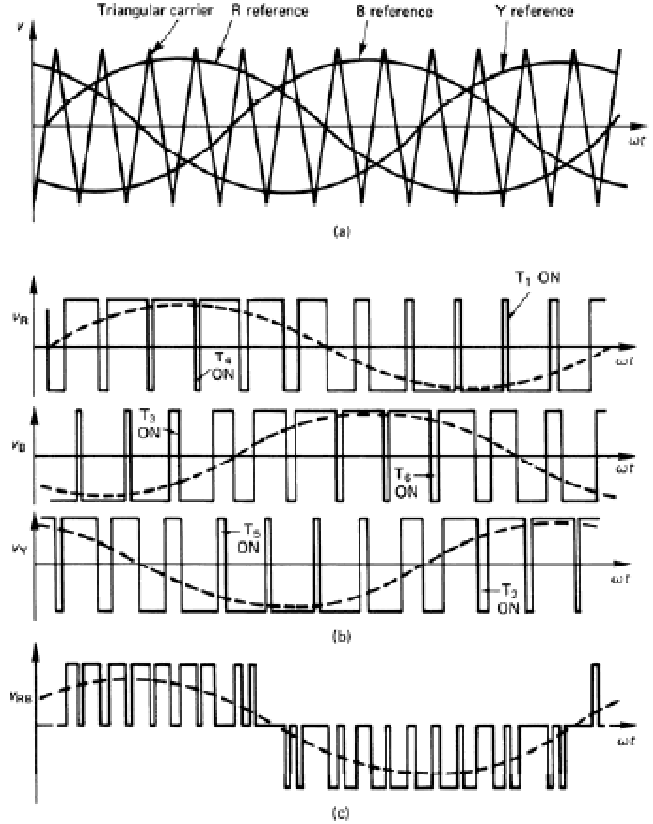


Figure 14.12. *Naturally sampled pulse-width modulation waveforms suitable for a three-phase bridge inverter: (a) reference signals; (b) conducting devices and fundamental sine waves; and (c) one output line-to-line voltage waveform.*

Reference waveforms displaced by 120^0

Here output Is shown for a grounded centre point on the DC supply

The load sees the line voltage i.e V_a-V_b

DC rail utilisation

- The ac peak output line voltage is limited to 0.866 V_{DC} supply. This compares with a single phase H-Bridge which can achieve a peak of V_{DC}
- **Te**chniqies exist that can achieve a higher AC output from the same DC supply, thereby improving DC voltage utilization

Third Harmonic Injection

- The load only sees the line voltage, therefore third harmonic components (and multiples) in the phase voltage are not seen by the load.

- We can add these ‘triplin’ harmonics to the phase modulating waveform without changing the output. This can achieve increased output for the same DC supply rail.

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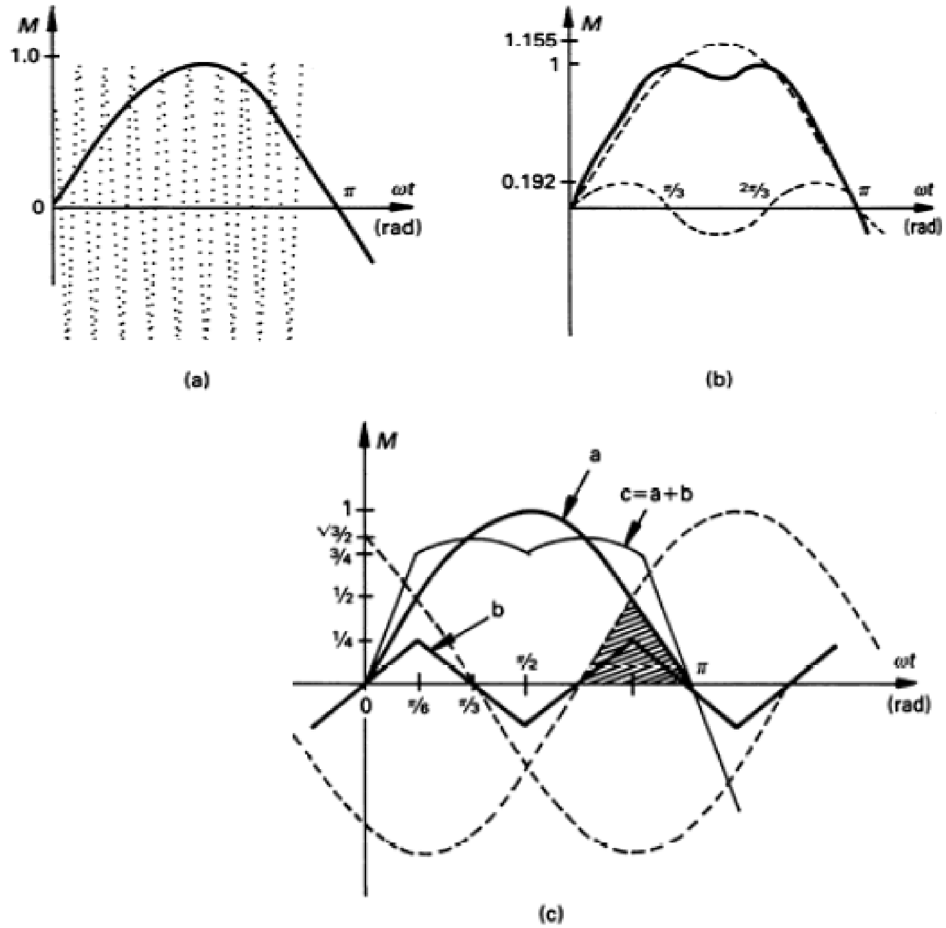

Figure 14.21. *Modulation reference waveforms: (a) sinusoidal reference, sin ωt; (b) third harmonic injection reference, sin ωt + $\frac{1}{6}$sin 3ωt; and (c) triplen injection reference, sin ωt + (1/√3π){9/8sin3ωt - 80/81sin9ωt + . . .} where the near triangular waveform b is half the magnitude of the shaded area.*

The fundamental can exceed the carrier range without saturating the total phase modulation

Space Vector Modulation.

Space Vector modulation is based on a vector representation of the possible switch combinations.

Space vector modulation assigns a vector direction to each of the phase modulation quantities.

Each switch combination will produce a vector which lies on one of 12 axes.

Space vector modulation is widely used in drive systems due its links with MMF control in AC machines.

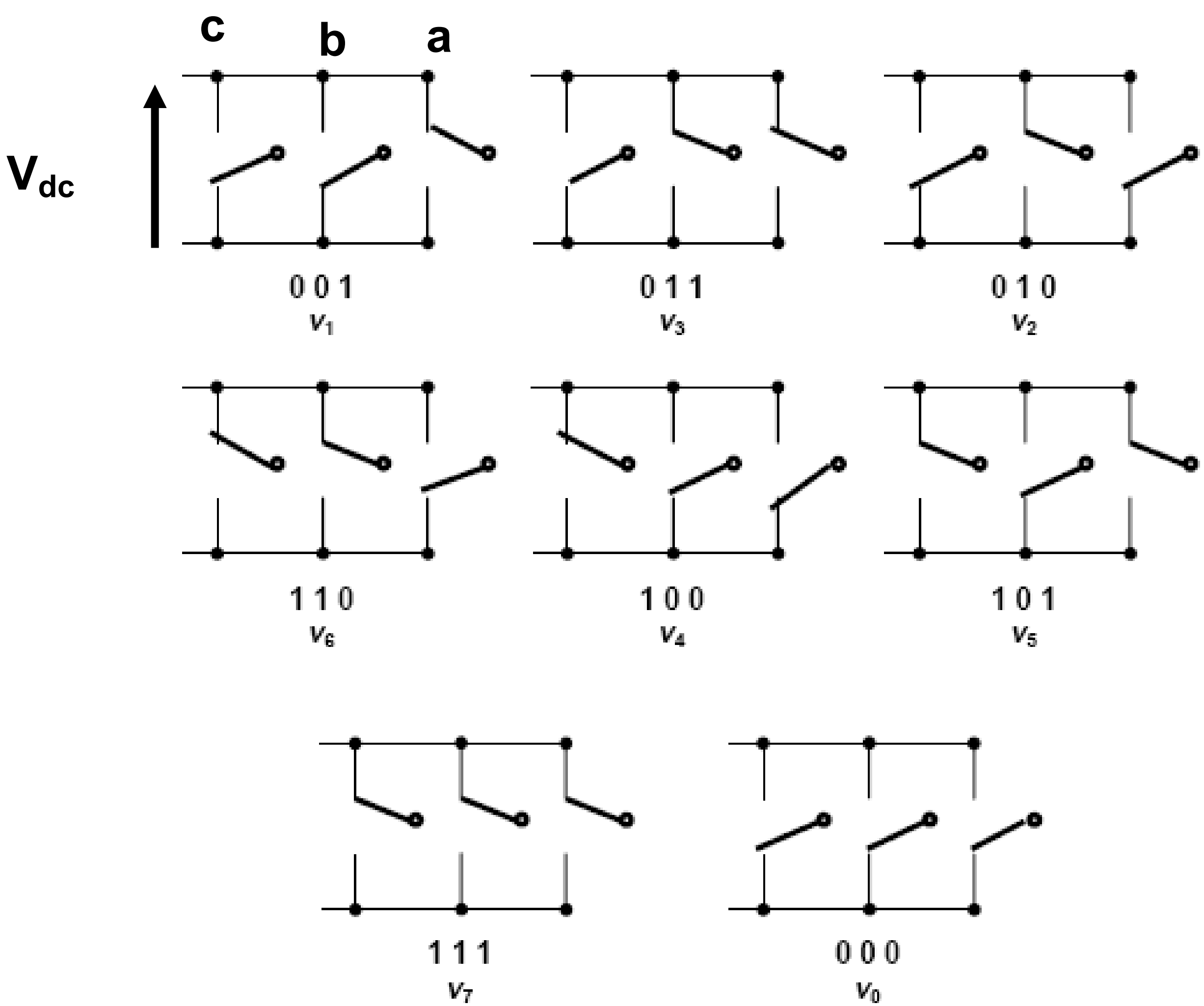

Figure 14.22. *Instantaneous output voltage states for the three legs of an inverter.*

Space Vector Modulation