What we have studied so far

With Prof Lianping Hou

- Electric Circuits
- Power Switches
- Uncontrolled and Controllable Switches
- Heatsinks

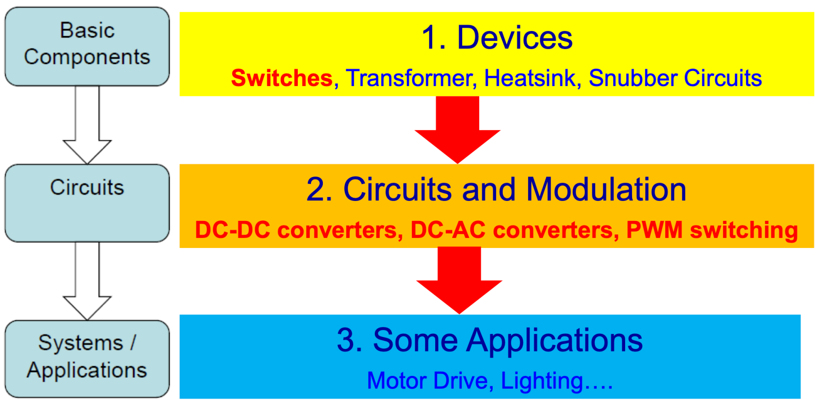
Since Week-8

- Snubber Circuits
- Switched Mode Power Supplies (DC converters)
- DC-AC converters (Inverters)

To do

- PWM Inverters
- Applications and Systems
- Revision of Numerical Questions

Course Structure



Today's Lecture

- PWM Inverter
- Types of PWM Inverter
- Numerical Problems

Power Electronics

PWM Inverters

(脉宽调制逆变器)

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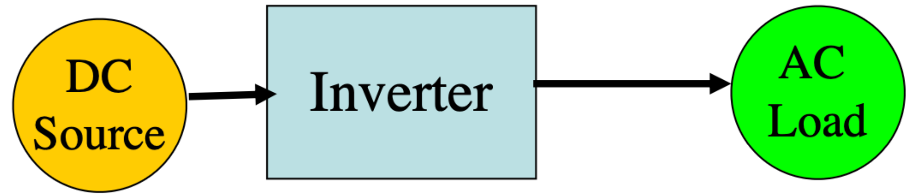
Please read Chapter 8 in the textbook

Fundamentals

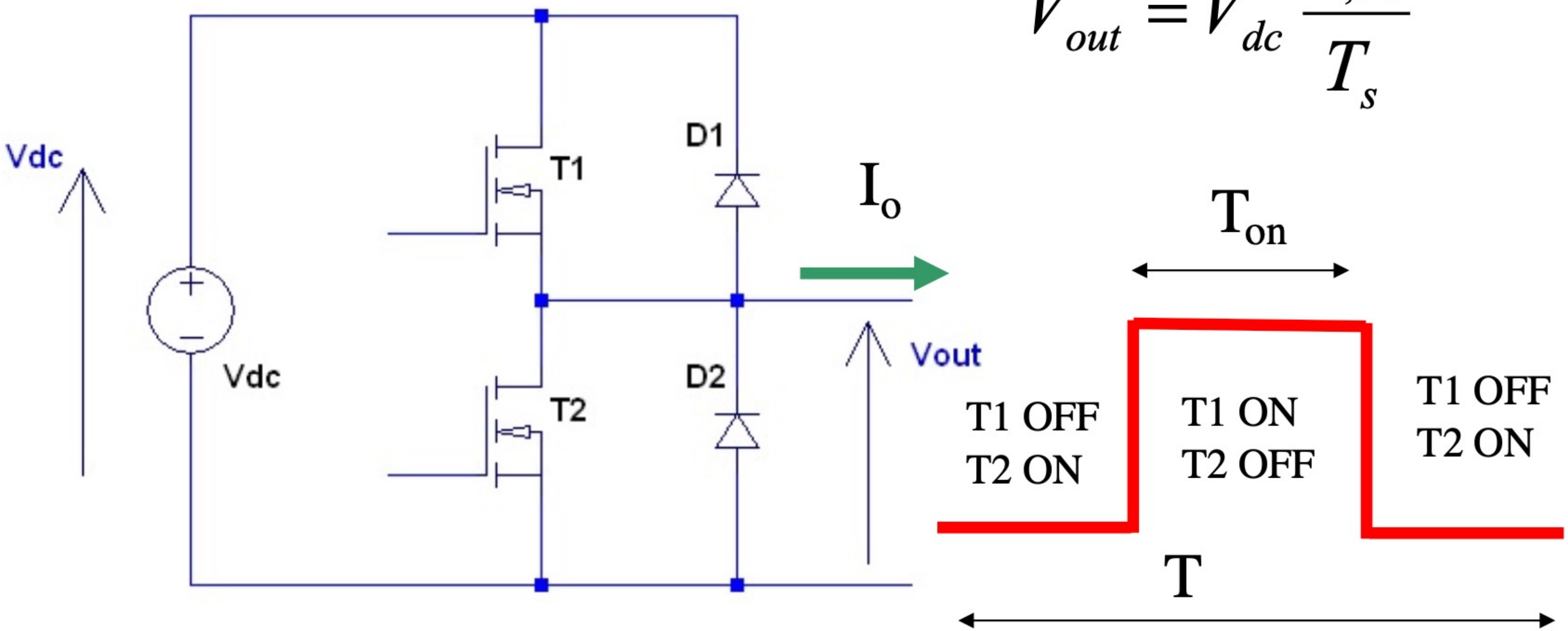


- DC-AC Converters are known as inverters
- Role is to convert a DC signal to AC
- Ideally, output should be sinusoidal.
- In reality, they are non-sinusoidal and contain harmonics
- This is fine for low and medium power applications
- Divided into two main types
    - Single Phase
    - Three Phase
- Semiconductor devices typically used
- The basic building block is the two 'Bridge' circuit

https://www.youtube.com/watch?v=qVeERT4nyz8

Bridge Circuit

$$V_{out} = V_{dc}\frac{t_{1,on}}{T_s}$$

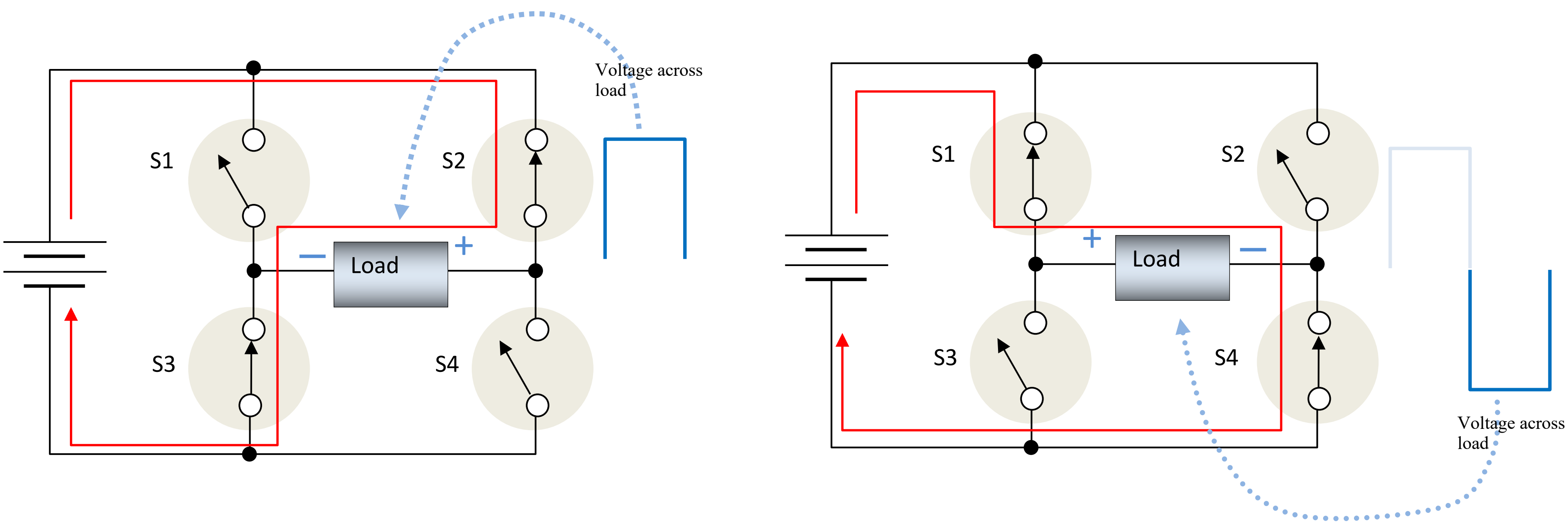


$I_0 > 0$ T1 and D2 are active

$I_o < 0$ D1 and T2 are active

Inverters with an H-Bridge

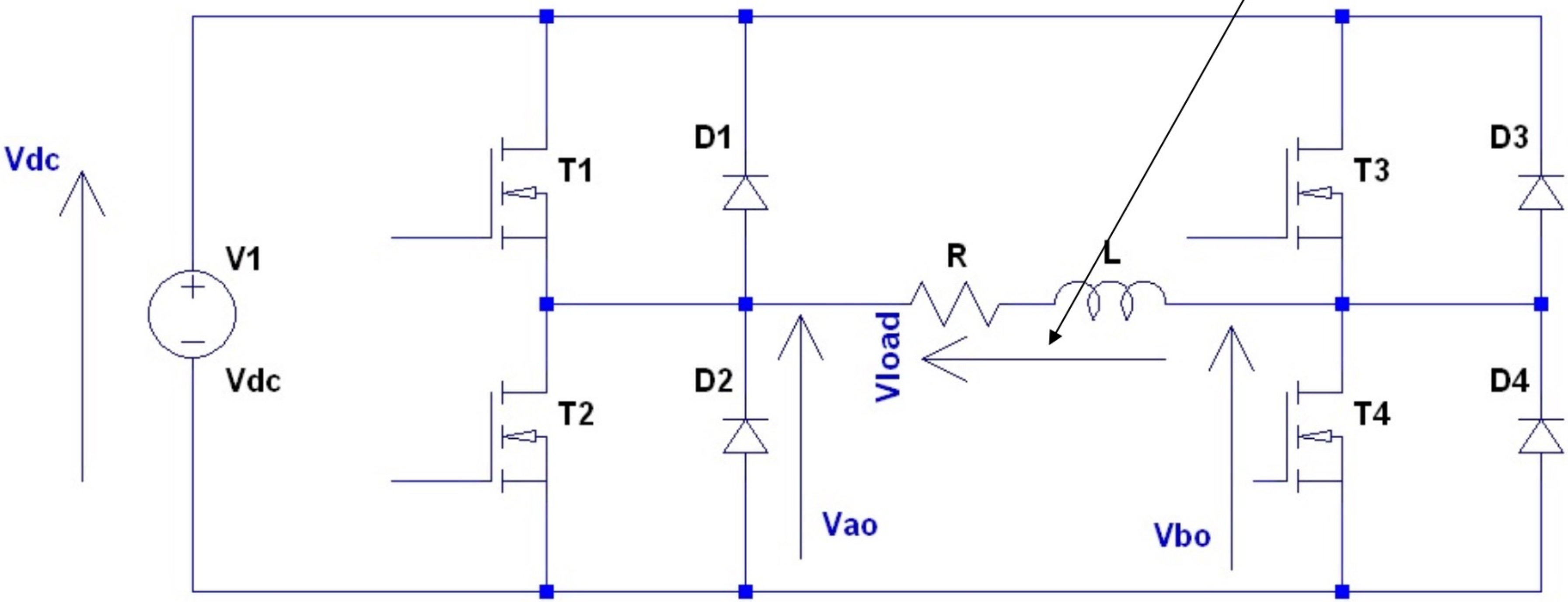
An H-bridge can produce a basic bipolar square wave. A variation of this circuit is used with other circuitry to produce a sine wave using pulse-width modulation (PWM).



Single-phase H-bridge

- Two inverter legs connected in parallel.
- Bi-directional load voltage and current.

$$V_{load} = V_a - V_b$$



- For low- and medium-power applications, square-wave or quasi- square-wave voltages may be acceptable; and for high-power applications, low distorted sinusoidal waveforms are required.

- With the availability of high-speed power semiconductor devices, the harmonic contents of output voltage can be minimized or reduced significantly by switching techniques

Better Quality AC output

How do we obtain a better quality AC waveform?

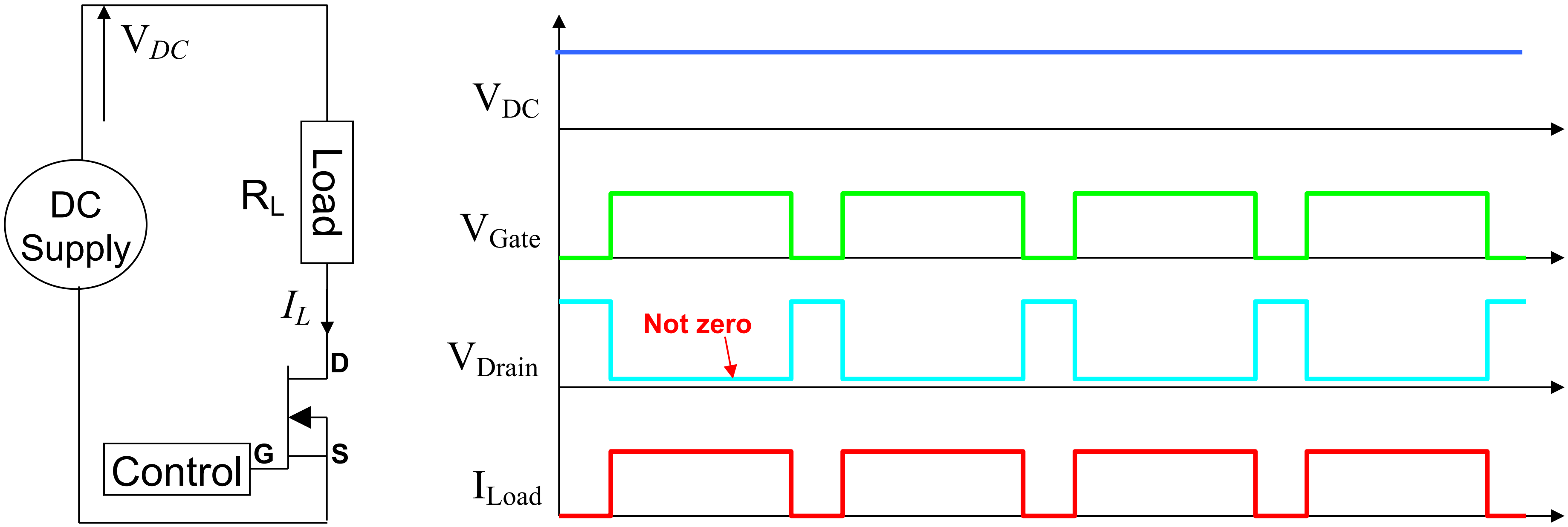
NOTE:

- 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 ?

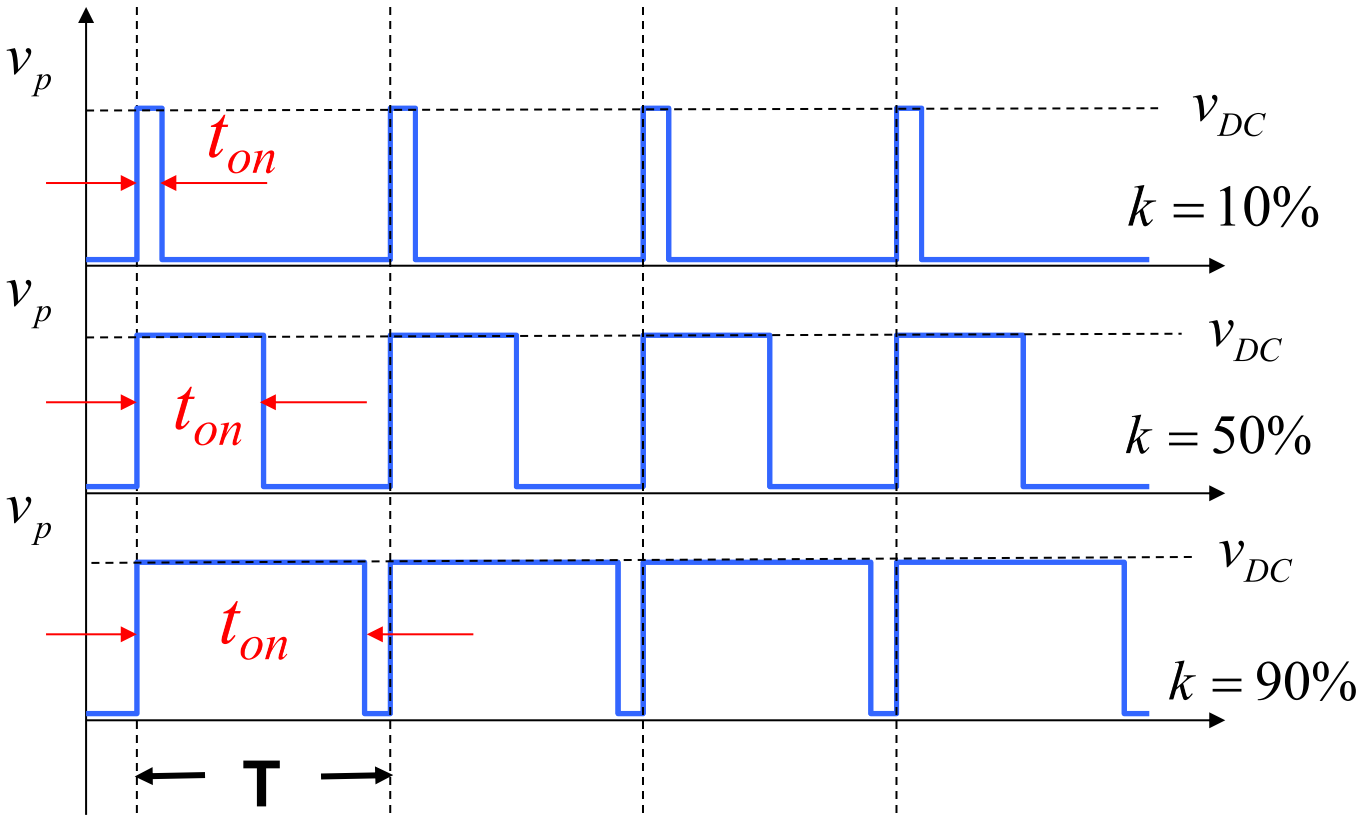
PWM Switching



Pulse Width Modulation (PWM). By changing the width (or duty cycle) of the gate pulse in relation to the operating frequency we can linearly change the average voltage value on the load.

PWM is actually developed for fully-controlled switches e.g. MOSFET, GTO,…

Periodic PWM Waveforms



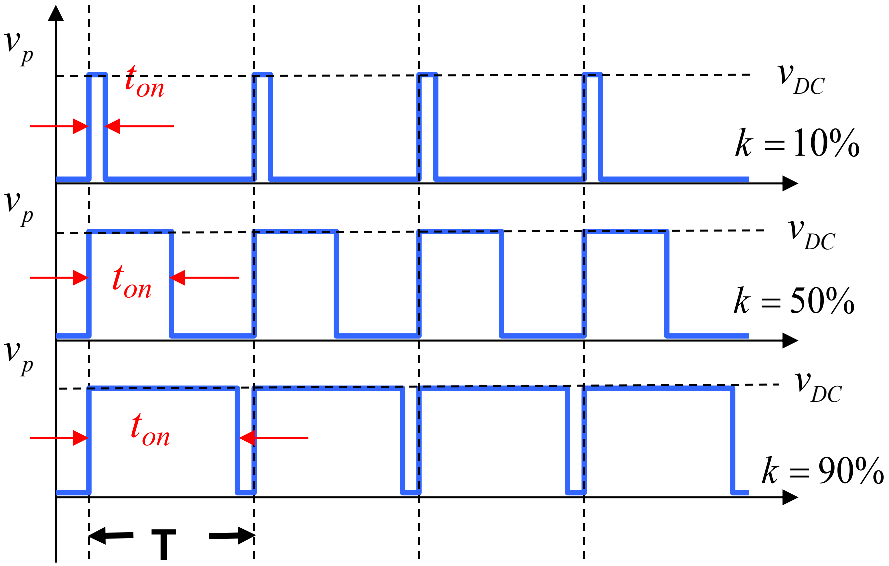
$$\text{Duty Cycle: } k = \frac{\text{On time}}{\text{Period}} = \frac{t_{on}}{T}$$

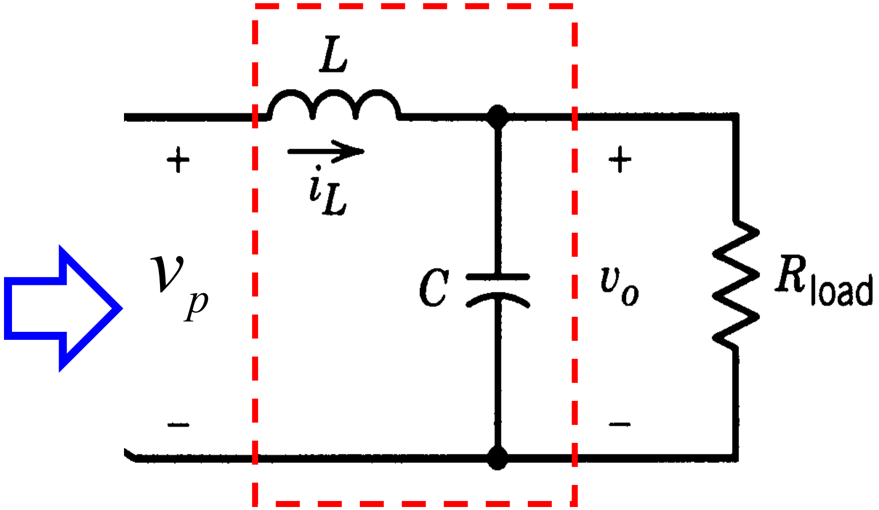
Average Load Voltage

$$v_{p(avg)} = k v_{DC}$$

High frequency (e.g. > 20kHz) voltage pulse train is ok for heating or even lighting, but is unacceptable for constant DC power supplies.

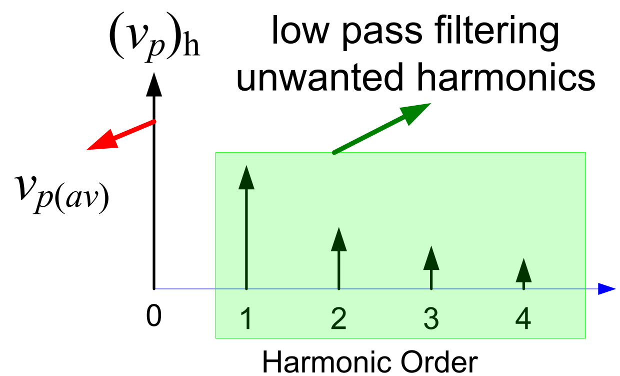
Smoothed PWM Output





low-pass filter

Low pass LC filter smoothed the pulse voltage v_p into a constant dc voltage v_o



$$\boxed{v_o \approx v_{p(avg)} = kv_{dc}}$$

The higher the switching frequency is, the smaller the size and weight of low pass filter LC can be, and more smoothed the output dc voltage v_o is.

Fourier Series

Fourier Series: Any periodic signal $f(x)$ can be decomposed into the sum of a (possibly infinite) set of harmonics (*i.e.* sines and cosines) plus its dc mean value.

$$f(x) = \underbrace{\tfrac{1}{2} a_0}_{\text{Mean value}} + \underbrace{\sum_{n=1}^{\infty} a_n \cos(n x) + \sum_{n=1}^{\infty} b_n \sin(n x)}_{\text{Harmonics}},$$

$$a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x)\, d x$$

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos(n x)\, d x$$

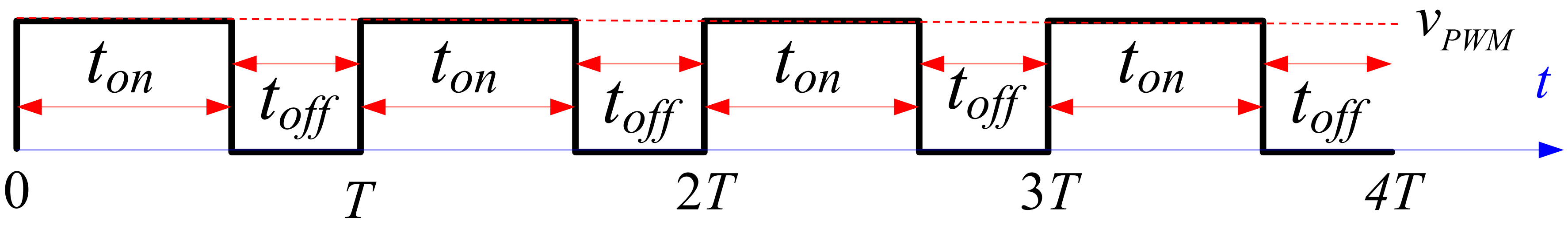
$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin(n x)\, d x$$

A low pass filter can easily remove harmonics. Thus the output voltage can be conveniently regulated by tuning duty cycle k. It is simple and easy-implementation.

Switching Strategies

How to generate duty-cycle-controllable rectangular pulse train for switching ON/OFF?

1. Constant switching frequency with variable ON time and OFF time (i.e. *variable duty ratio*)



$$switching\ period: \quad T = t_{on} + t_{off}$$

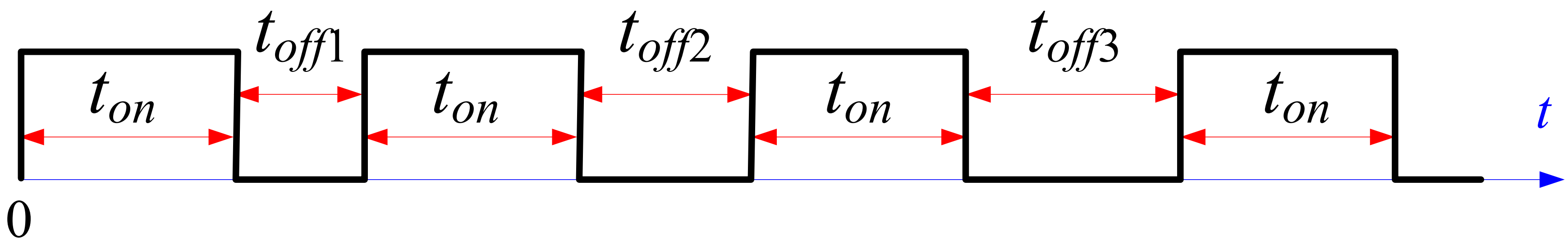
$$duty\ ratio: \quad k = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T}$$

It is called Pulse-Width-Modulation (**PWM**). PWM signal has constant amplitude v_{PWM}.

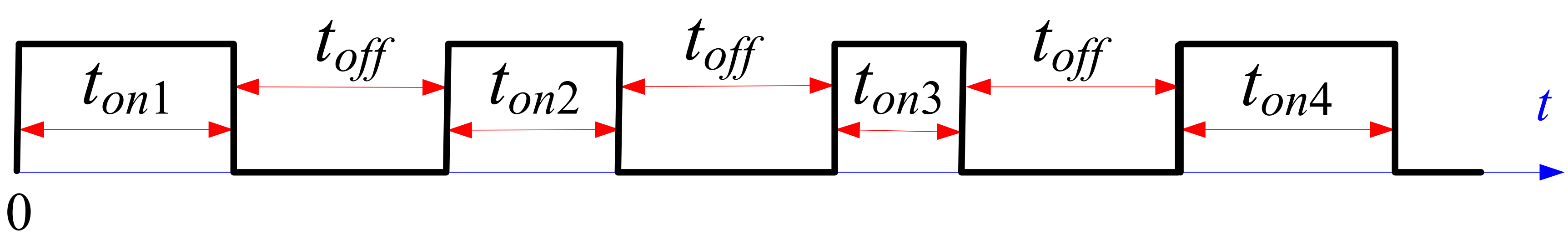
Variable Frequency Switching

2. Non-constant switching frequency, but either ON time or OFF time is held constant

Constant ON time



Constant OFF time



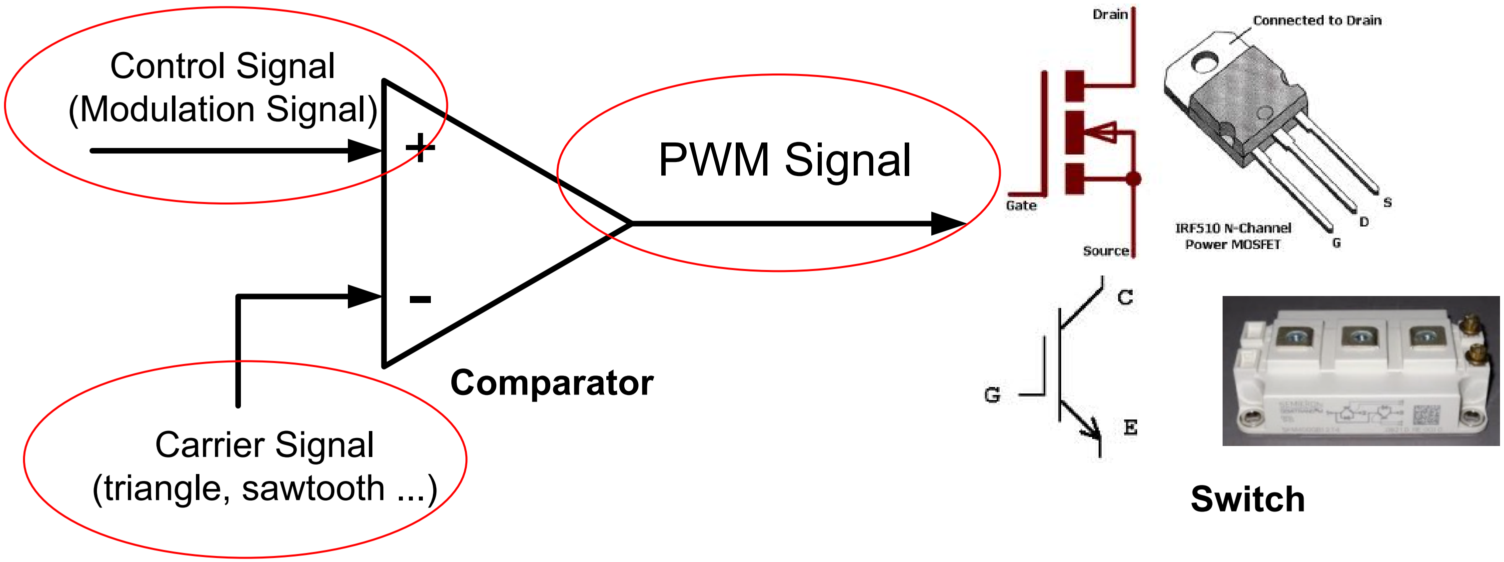
However, variable switching frequency leads to difficulty in designing filters to remove switching harmonics.

Switching Frequency

- Switch frequency (1/*Ts*) 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.

Check PWM switching and generation pdf

PWM Signal Generation

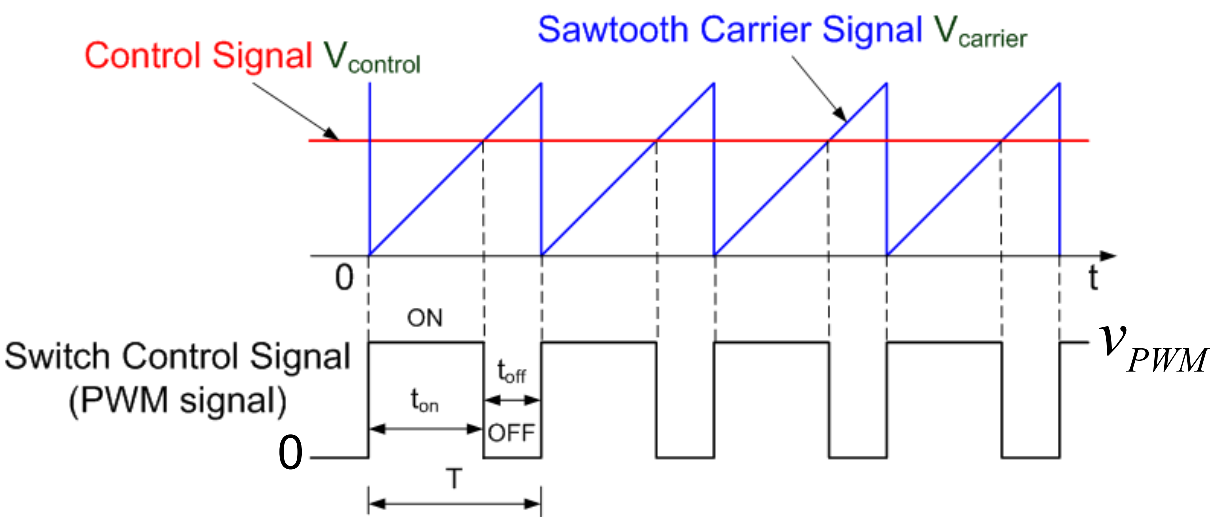


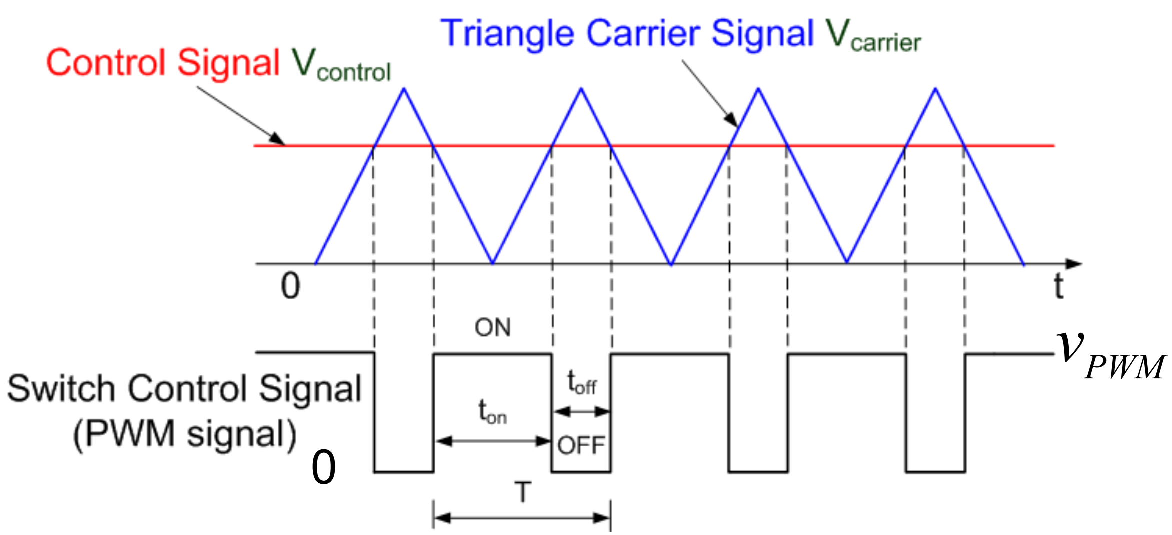
Pulse Width Modulation (PWM)

1. Constant (high) Switching (Carrier) Frequency
2. Carrier Frequency >> Control Signal Frequency
3. Control Signal Peak <= Carrier Signal Peak
4. Output Pulse Width is proportional to input control signal

Unipolar PWM Signal

Within one switching period, PWM signal is either positive or zero; or PWM is either negative or zero.





switching frequency:

$$f_s = \frac{1}{T_s};$$

duty cycle:

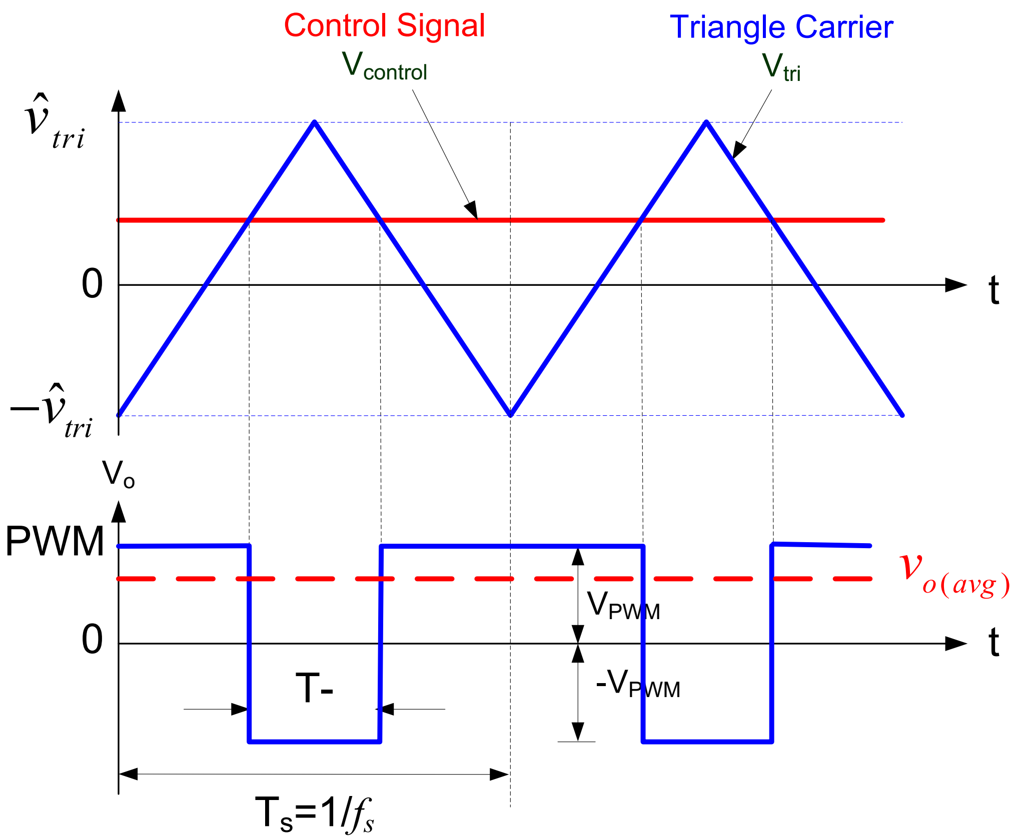
$$k = \frac{t_{on}}{T_s} = \frac{V_{control}}{\hat{V}_{carrier}}$$

average output:

$$v_{o(avg)} = k v_{PWM}$$

Bipolar PWM Signal

Within one switching period, PWM signal is either positive or negative.



$$T_s = \frac{1}{f_{tri}}, T_+ + T_- = T_s$$

$$v_{o(avg)} = \frac{T_+}{T_s} v_{PWM} - \frac{T_-}{T_s} v_{PWM}$$

$$= \frac{2T_+ - T_s}{T_s} v_{PWM} = \frac{v_{control}}{\hat{v}_{tri}} v_{PWM}$$

$$= k v_{PWM}$$

Duty Cycle :

$$\boxed{k = \frac{2T_+ - T_s}{T_s} = \frac{v_{control}}{\hat{v}_{tri}}}$$

PWM Amplifier

$$v_{o(avg)} = k v_{PWM} = \left(\frac{V_{control}}{\hat{V}_{carrier}} \right) v_{PWM} = \left(\frac{v_{PWM}}{\hat{V}_{carrier}} \right) V_{control}$$

1. Neglecting high order harmonics, PWM conversion is a linear amplifier. The mean value of output PWM signal for each switching period is equivalent to an amplified control signal with amplifier gain of $v_{PWM}/V_{carrier(peak)}$.

2. In fact, control signal $V_{control}$ can be either a sinusoidal signal for DC-AC PWM conversion and a dc signal for DC-DC PWM conversion.

Sinusoidal PWM

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

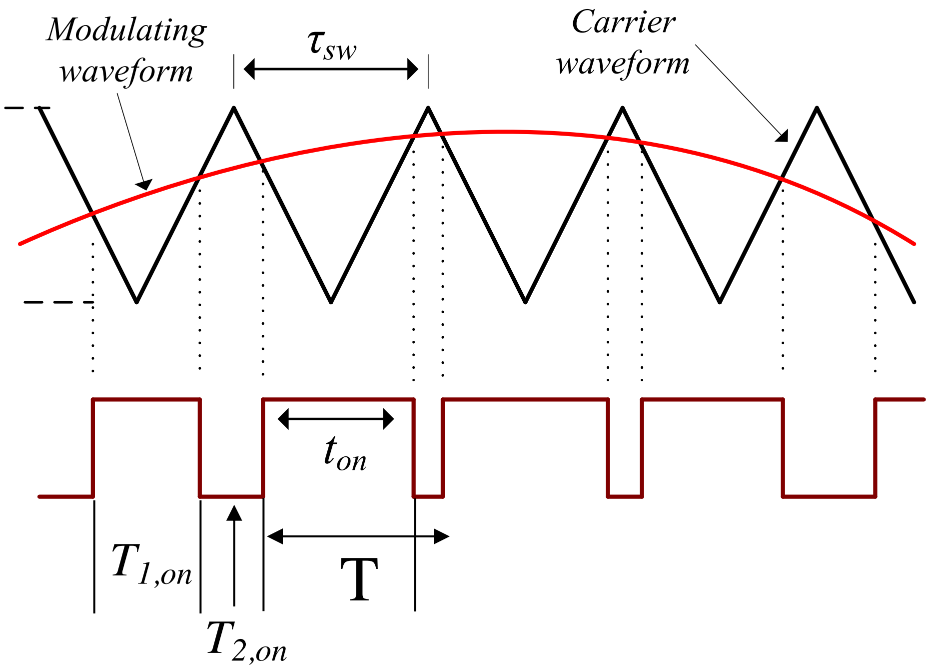
By controlling this instantaneous average to track a sinusoidal reference it is possible generate an AC (Fundamental) voltage at the bridge-leg output.

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

$$0 \leq M \leq 1$$

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.

Basic Single Phase PWM

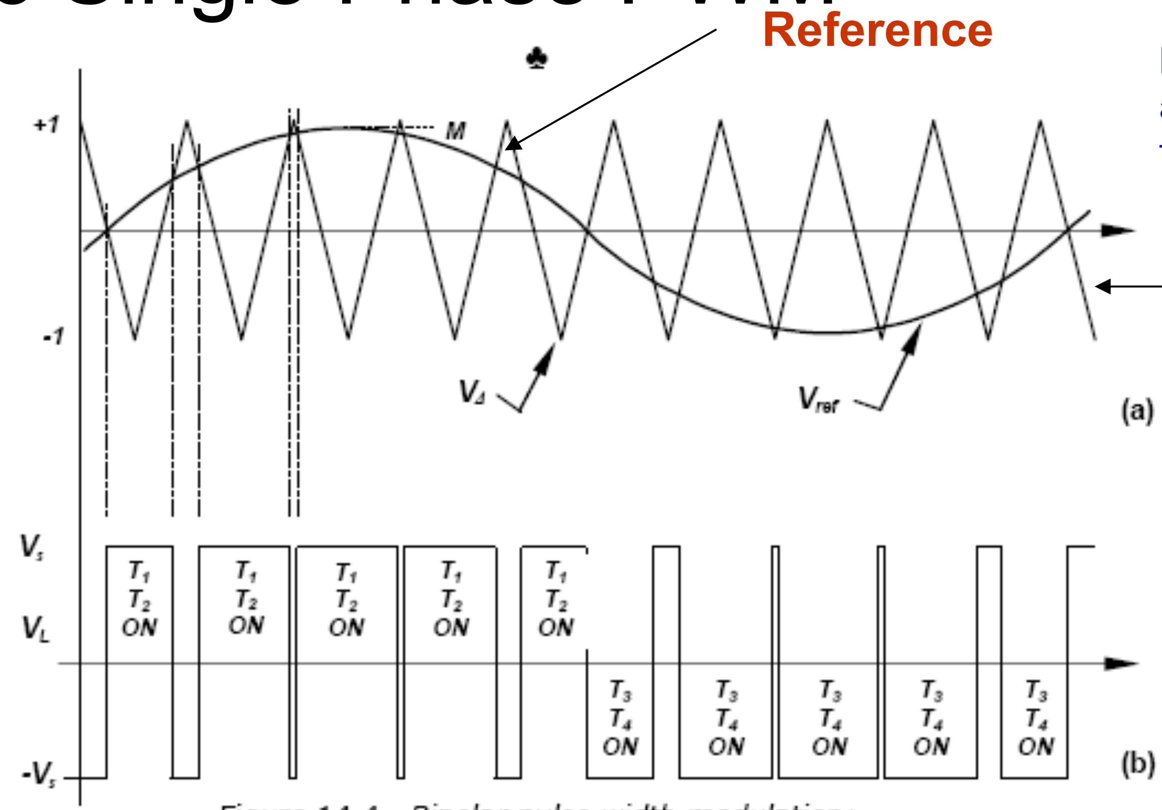


Figure 14.4. *Bipolar pulse width modulation:*
(a) carrier and modulation waveforms and (b) resultant load pwm waveform.

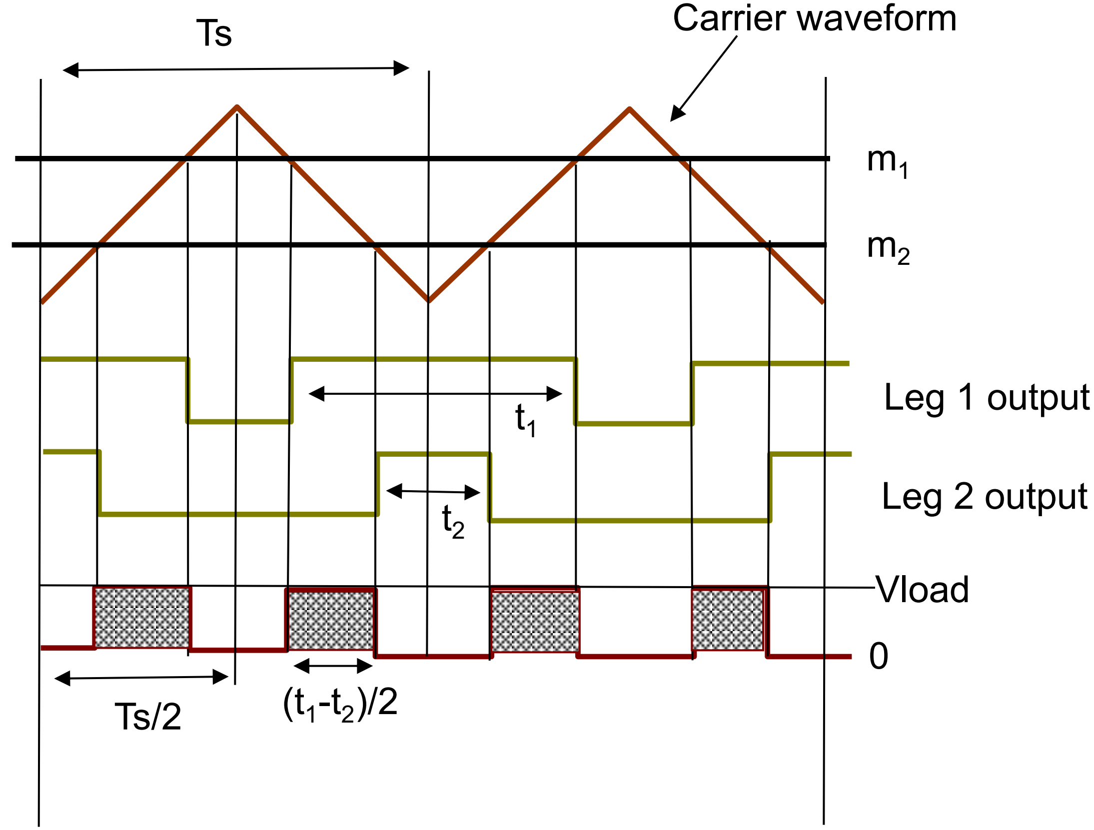
PWM produces harmonics around the switching frequency (1/T)

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

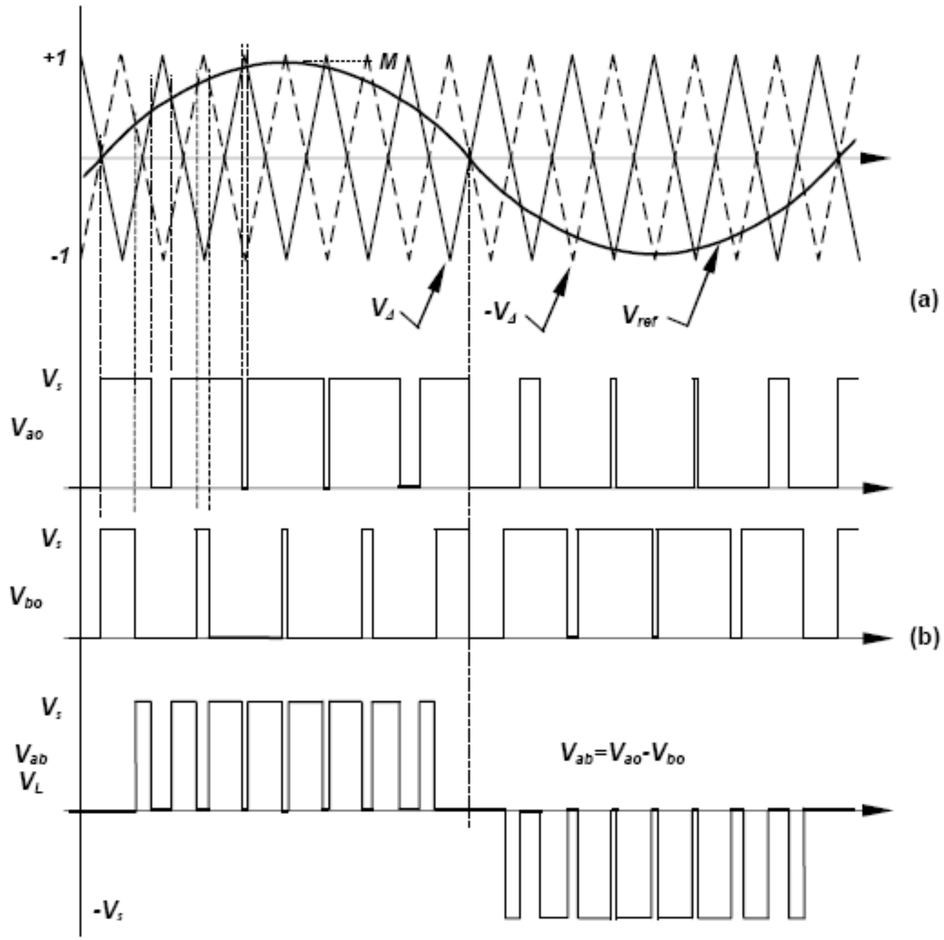


Figure 14.5. *Multilevel (3 level) pulse width modulation: (a) carriers and modulation waveforms and (b) resultant load pwm waveforms.*

Single modulating Waveform and inverted carrier

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

Two Level, three phase, PWM Inverter

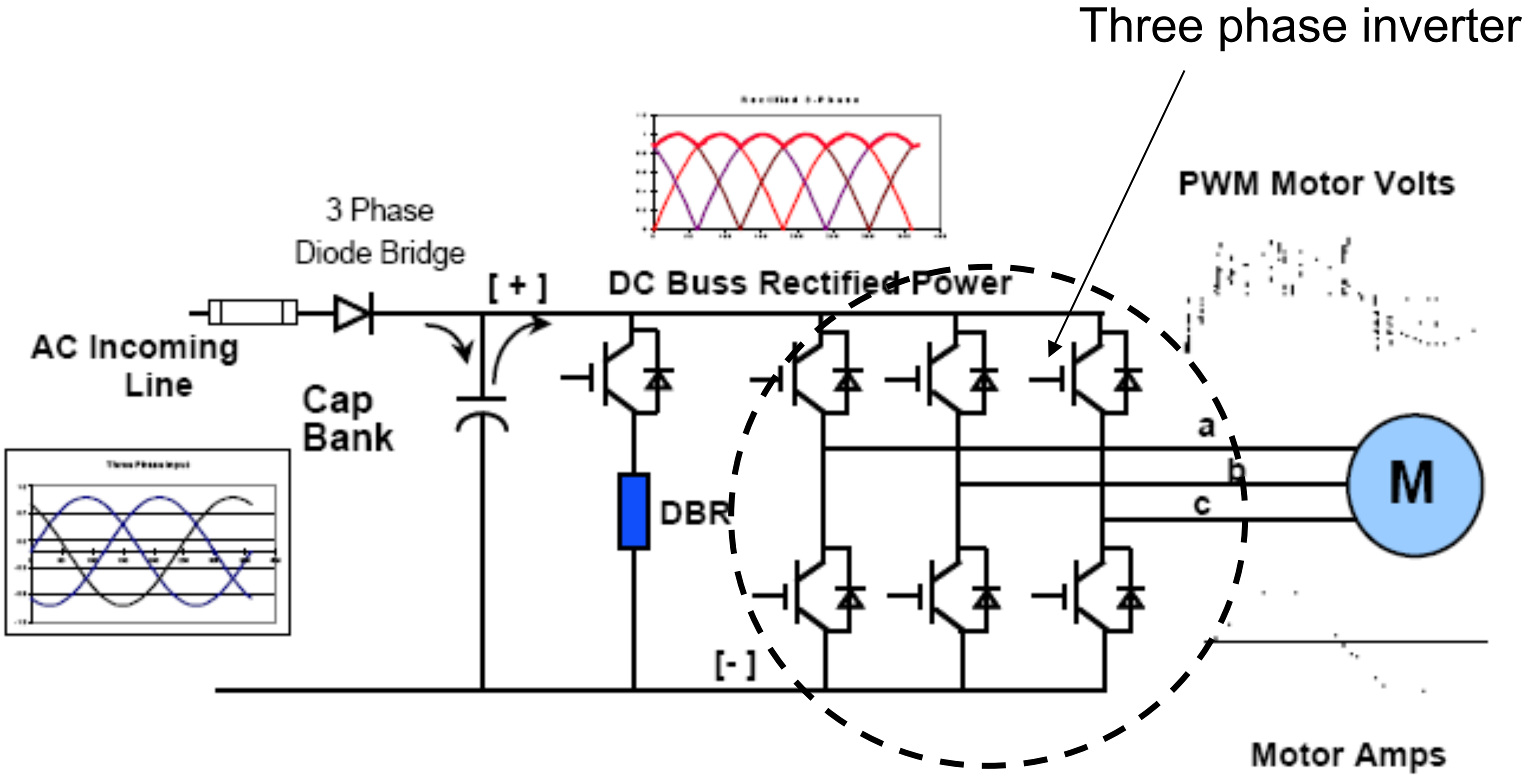


Figure 16. Two-Level PWM IGBT Drive

Source TMGE website

Three Phase Modulation

Reference waveforms displaced by 120^0

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

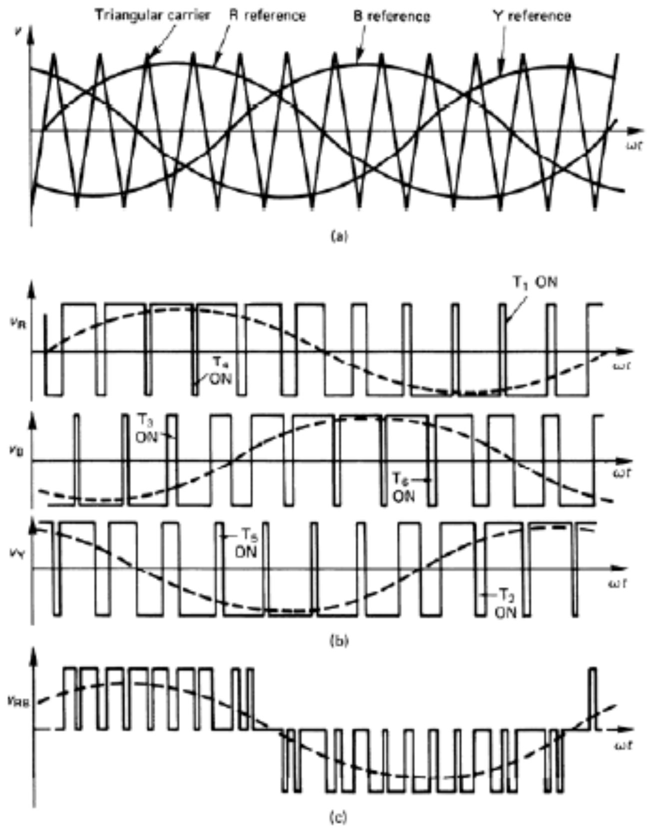


Figure 14.12. *Naturally sampled pulse-width modulation waveforms suitable for a three-phase bridge inverter: (a) reference signals; (b) conducting devices and fundamental sine waves; and (c) one output line-to-line voltage waveform.*

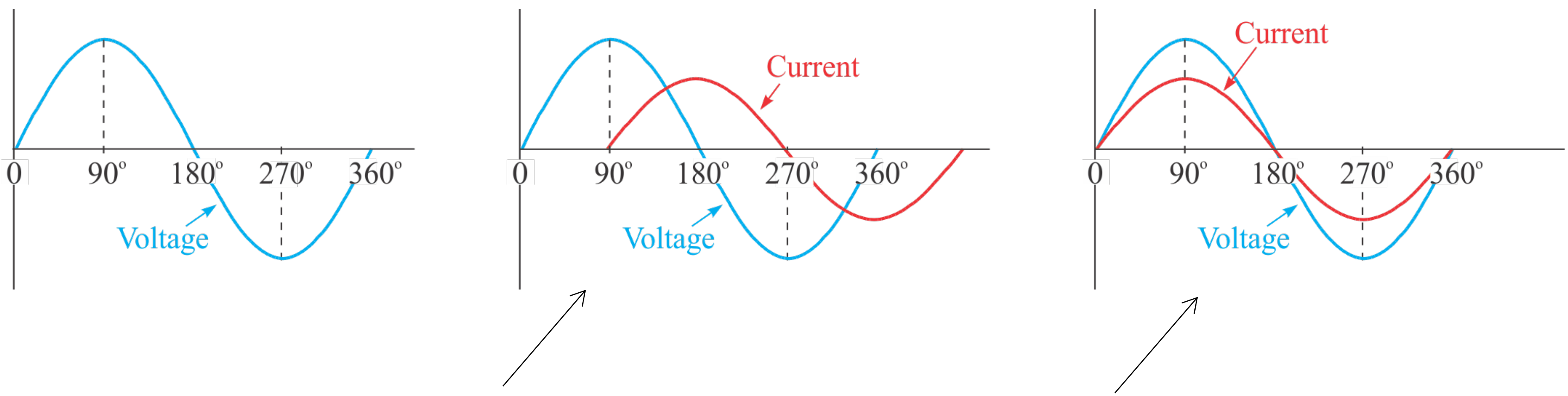
The load sees the line voltage i.e V_a-V_b

Inverter Functions

When a reactive load is connected to a source, the voltage and current shift in phase, which causes a reduction in the true power that can be delivered. To avoid this, some inverters can correct for power factor.

$$PF = \cos(\theta)$$

$$P_a = \sqrt{P_{\text{true}}^2 + P_r^2}$$

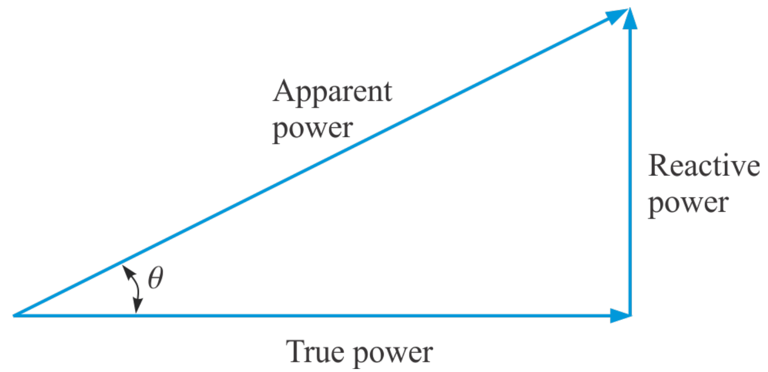


power factor = 0

power factor = 1

Inverter Functions

The power relationship between true power, reactive power, and apparent power can be illustrated with a right triangle.



Example

(a) What is the apparent power if the true power is 60 W and the reactive power is 30 VAR?

(b) What is the phase angle?

Solution

(a) $P_a = \sqrt{P_{\text{true}}^2 + P_r^2} = \sqrt{(60\text{ W})^2 + (30\text{ VAR})^2} = 67.1\text{ VA}$

(b) $\theta = \cos^{-1}\left(\dfrac{\text{True power}}{\text{Apparent power}}\right) = \cos^{-1}\left(\dfrac{60\text{ W}}{67.1\text{ VAR}}\right) = 26.5^{\circ}$

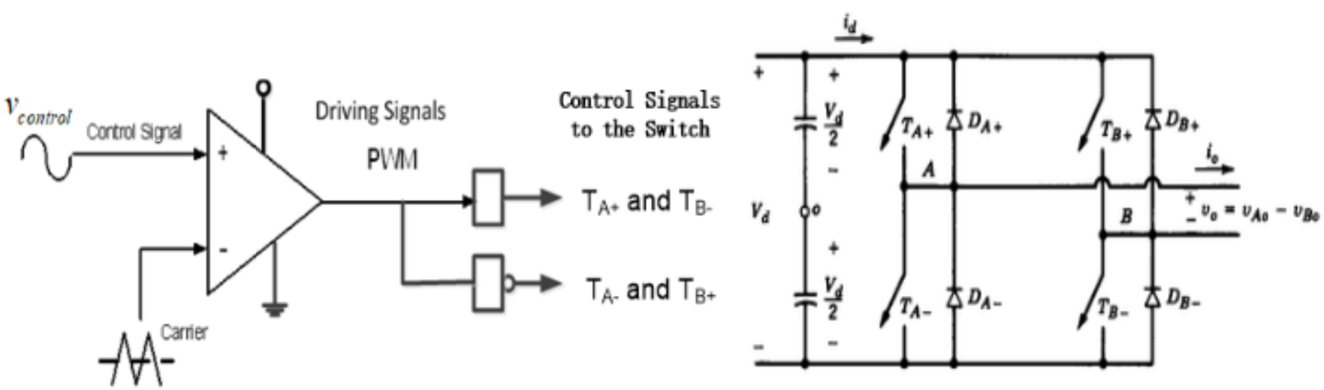
Problem - 1

Figure below shows a single-phase PWM converter with its bipolar PWM drive circuit, where and dc bus voltage V_d=100V, the carrier frequency $f_{carrier}$ is much higher than the control signal frequency f, the control signal $v_{control} = m_a \sin(2\pi ft)$, and the peak values of the triangle carrier signal are 1 and -1.

(a) When $m_a = 0.5$, determine the output voltage v_o of the single-phase converter. We assume the high frequency harmonic components in the voltage v_o is neglected.

(b) When $m_a >> 1$, what will happen to the converter? Indicating its benefits and disadvantages.

(c) If the control signal is changed to $v_{control} = 0.6$ V, determine the average output voltage v_o of the single-phase converter. We assume the high frequency harmonic components in the voltage v_o is neglected.



Problem - 1

Solution:

(a) $v_{out} = \frac{v_{control}}{\hat{v}_{carrier}} \times v_d = 50\sin(2\pi ft)$ *[3]*

(b) *If* $m_a >> 1$*, overmodulation, the RMS value of output voltage reach its maximum value, however, unwanted harmonics distortions is very serious (may lead torque ripples of motor), switching frequency is the lowest [3]*

(c) *Vo=60V*

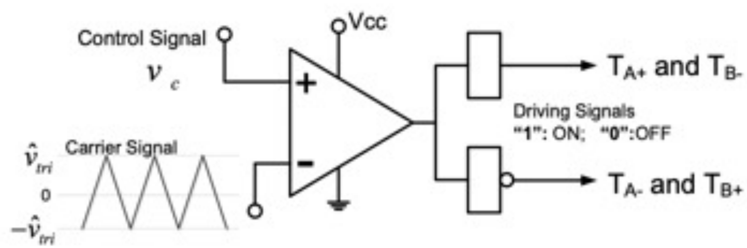
Problem-2

(b) Figure shows a H-bridge converter with its bipolar PWM drive circuit, where the carrier frequency f_c is much higher than the bandwidth ***BW*** of the output low-pass LC filter, and the bandwidth ***BW*** of the output low-pass LC filter is much higher than the control signal frequency f, i.e. $f_c \gg BW \gg f$,

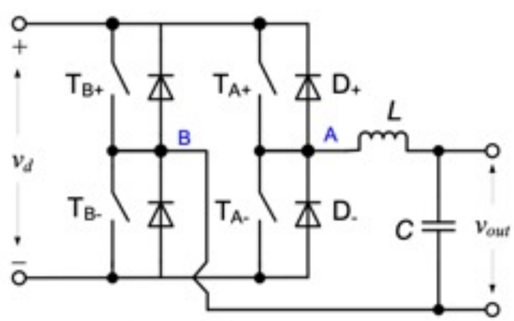
(i) If the control signal $v_c = \hat{v}_c \sin(2\pi ft)$ with $0 < \hat{v}_c \le \hat{v}_{tri}$, determine the approximate value of the output signal v_{out}.

(ii) If the control signal $v_c = -\hat{v}_c$ with $0 < \hat{v}_c \le \hat{v}_{tri}$, determine the approximate value of the output signal v_{out}

(iii) State what are the 'shoot-through' and corresponding precautions for the operation of H-bridge.



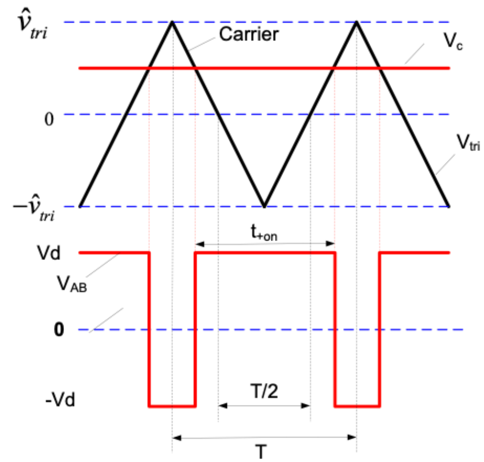
Bipolar PWM Drive Circuit



H-Bridge Converter

Solution-2

i) Over one switching period T, the bipolar PWM modulation figure is shown as follows



The positive output time t_{+on} of the PWM waveform V_{AB} is

$$t_{+on} = \frac{v_c - (-\hat{v}_{tri})}{\hat{v}_{tri} - (-\hat{v}_{tri})} T = \left(\frac{v_c}{\hat{v}_{tri}} + 1 \right) \frac{T}{2}$$

The negative output time t_{-on} of the PWM waveform V_{AB} is

$$t_{-on} = T - t_{+on} = \left(1 - \frac{v_c}{\hat{v}_{tri}} \right) \frac{T}{2}$$

From above two equations, the average value of the PWM output V_o over one switching period is

$$V_{AB(avg)} = \frac{1}{T} \left(v_d t_{+on} - v_d t_{-on} \right) = v_d \left(\frac{v_c}{\hat{v}_{tri}} \right)$$

Since the carrier frequency $f_c \gg$ the control signal frequency f and the bandwidth **BW** of the low-pass LC filter, such that $f_c \gg BW \gg f$, the high frequency harmonics will be filtered out.

Therefore, we have

$$v_{out} \approx V_{AB(avg)} = v_d \left(\frac{v_c}{\hat{v}_{tri}} \right) = v_d \frac{\hat{v}_c}{\hat{v}_{tri}} \sin(2\pi f t)$$

Solution (cont.)

ii)

$$v_{out} \approx V_{AB(avg)} = v_d \left(\frac{v_c}{\hat{v}_{tri}} \right) = -v_d \frac{\hat{v}_c}{\hat{v}_{tri}}$$

iii)

Two switches (T+, T-) of any inverter leg are not allowed to be turned on at the same time, otherwise dc side voltage source will be shorted (Shoot-Through).

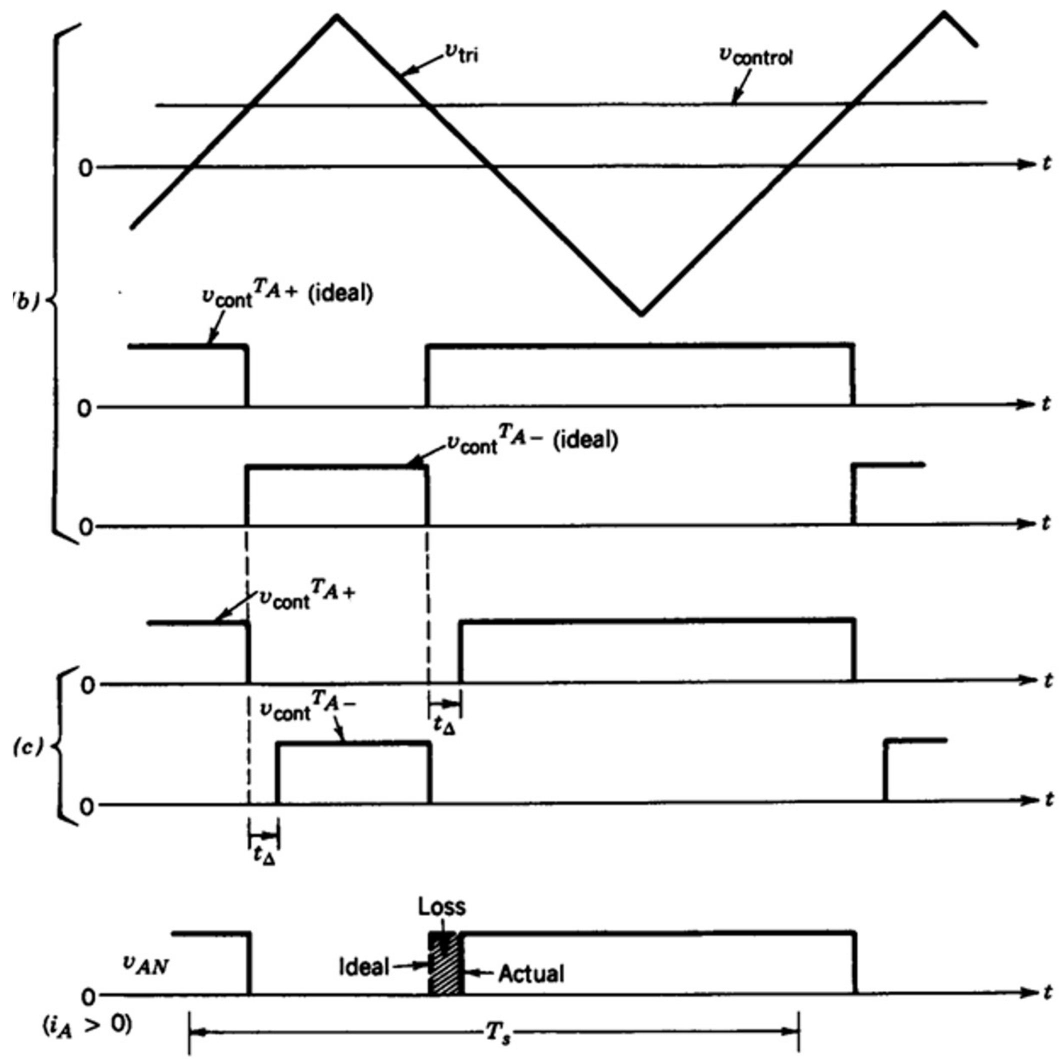
However, it will take some time for the switches to switching on/off. Therefore blank time (deadtime) must be inserted between the ON/OFF of T+ and T- to avoid shoot-through during the switching procedure.

Solution (cont.)

Two switches (T+, T-) of any inverter leg are not allowed to be turned on at the same time, otherwise dc side voltage source will be shorted

(Shoot-Through).

However, it will take some time for the switches to switching on/off. Therefore blank time (deadtime) must be inserted between the ON/OFF of T+ and T- to avoid shoot-through during the switching procedure.



Textbook Numerical for Previous Lectures

- Chapter 27 Snubber Circuits
  - 27-1
  - 27-2
  - 27-4
  - 27-5
  - 27-6
- Chapter 7 DC-DC Converters
  - 7-1
  - 7-2
  - 7-7
  - 7-8
  - 7-12
  - 7-13