Electronic Power Conversion

Switch mode DC-AC converters

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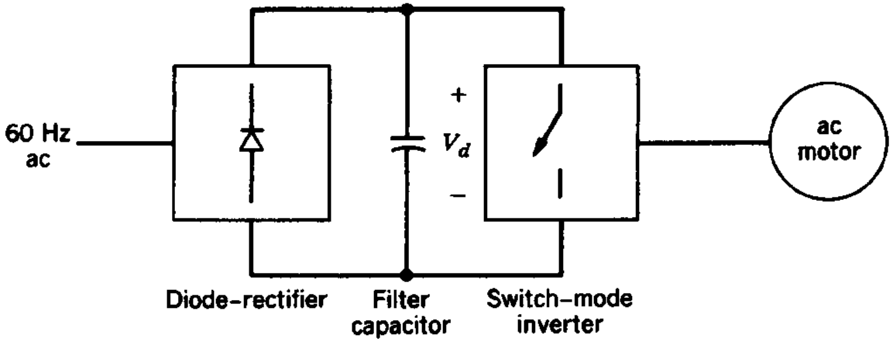
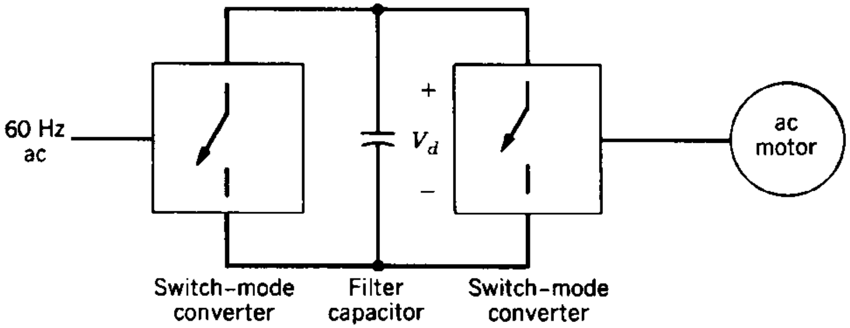
8. Switch mode DC-AC converters

- Applications:
  - AC motor drives
  - Uninterruptible Power Supplies (UPS)
- Categories of voltage-source inverters (VSI,VSC):
  - PWM inverters
  - Square-wave inverters
  - Single-phase inverters with voltage cancellation
  - Not considered: CSI (Current-Source Inverters, CSI)



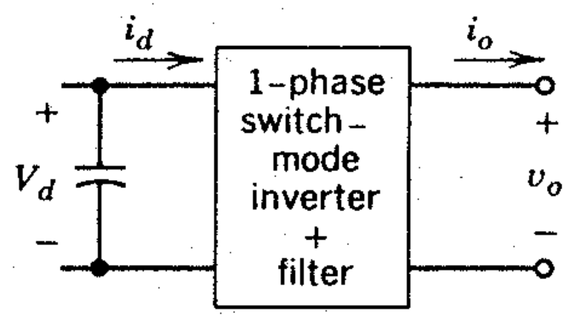
Uni-directional power

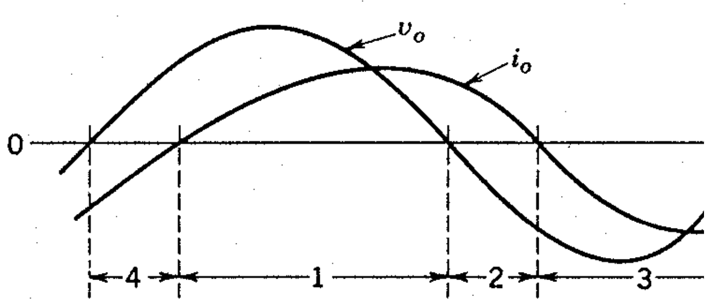


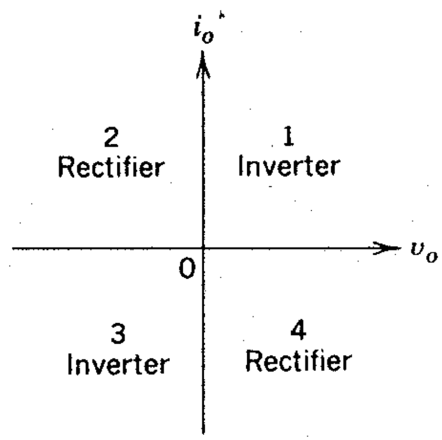
Bidirectional power (regenerative)

Switch-mode inverters – basics

- Requirement for instantaneous power flow:
  - Four-quadrant operation

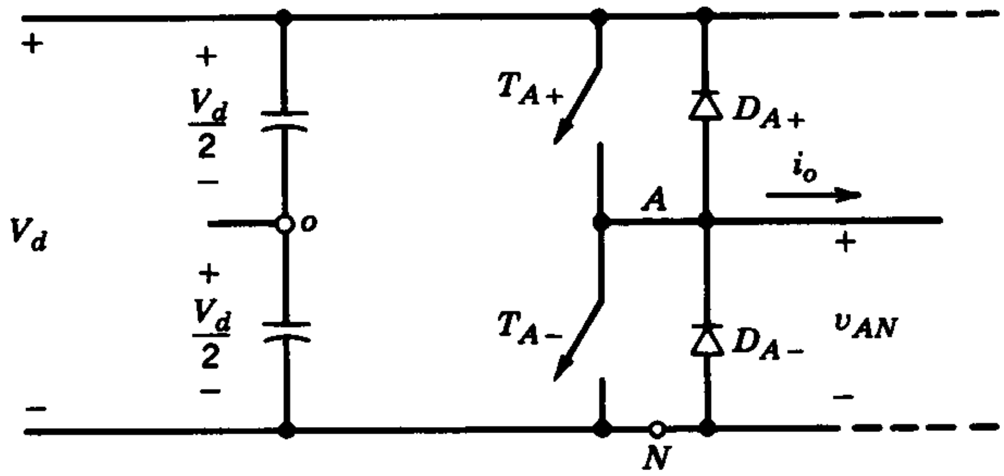




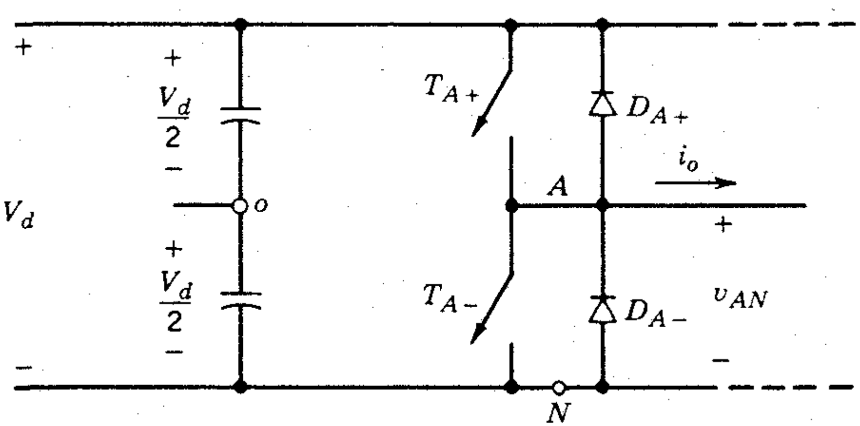


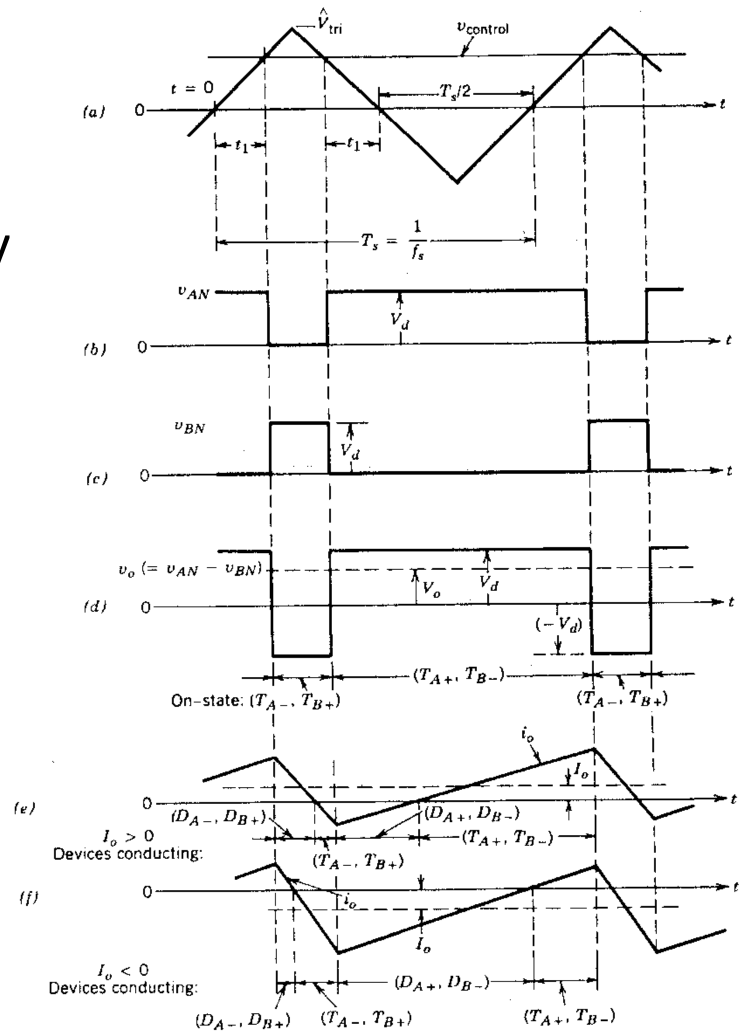
Phase leg (phase arm or NL: *fase tak*)

- All dc-ac topologies in Chapt. 8 based on phase arm
- Point 0 is taken as reference for voltage, mostly not physically available

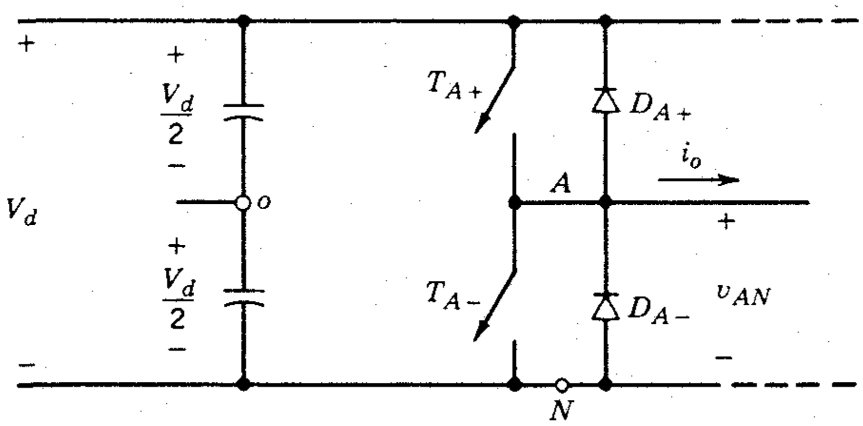


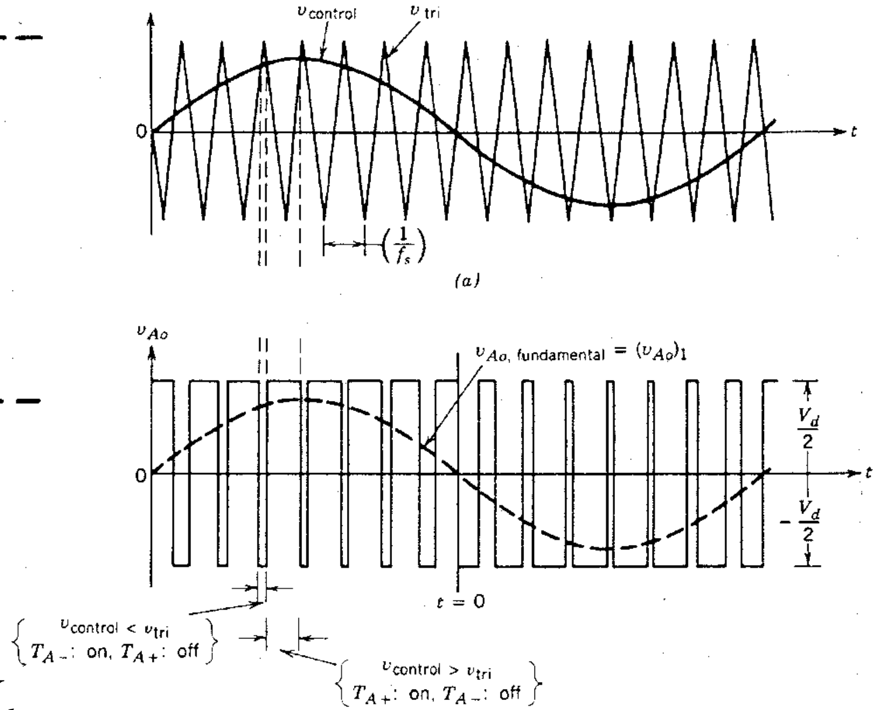
- Consider one leg of an H-bridge and v $v_{control}$ slowly





Synthesis of a Sinusoidal Output by PWM



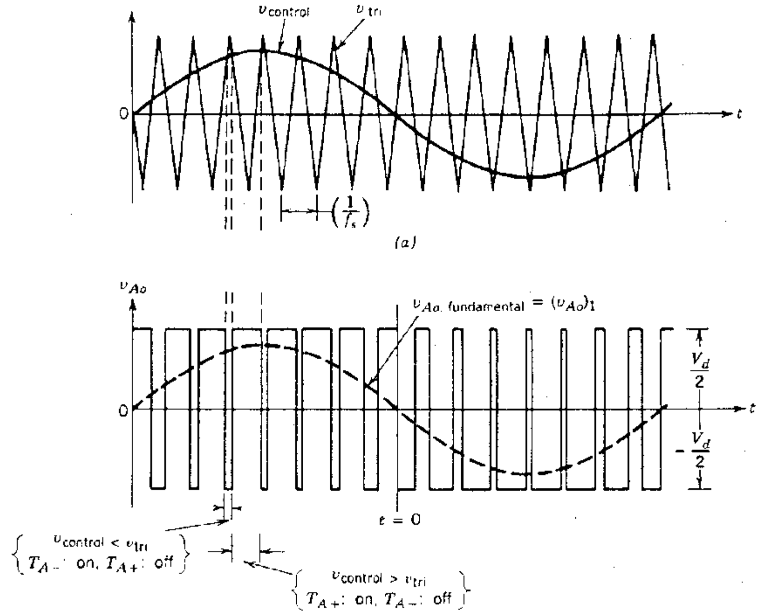


$v_{control} > v_{tri}$ T_{A+} is on ➔ $v_{A0} = \frac{1}{2} V_d$

$v_{control} < v_{tri}$ T_{A-} is on ➔ $v_{A0} = -\frac{1}{2} V_d$

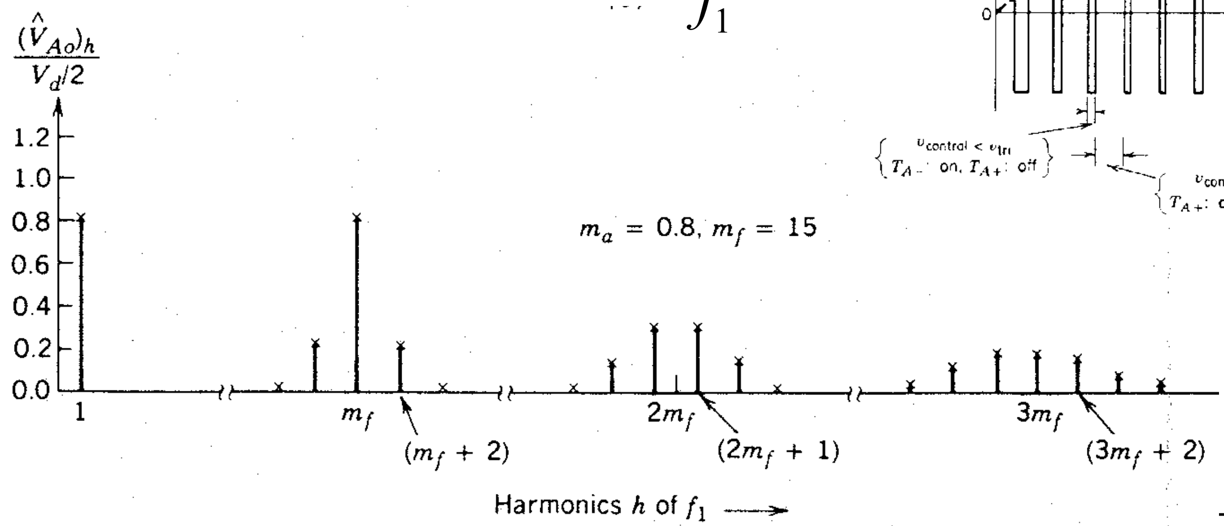
Spectrum

f_s - switching frequency, carrier frequency
f_1 - modulating frequency, fundamental frequency

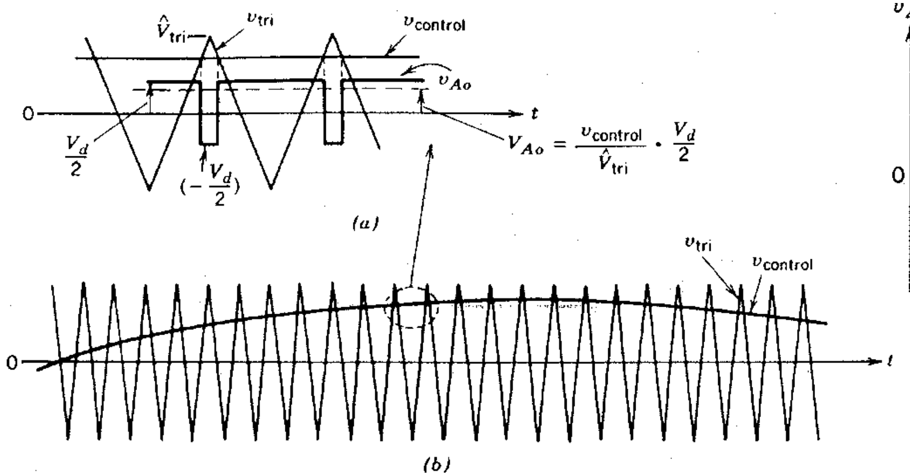


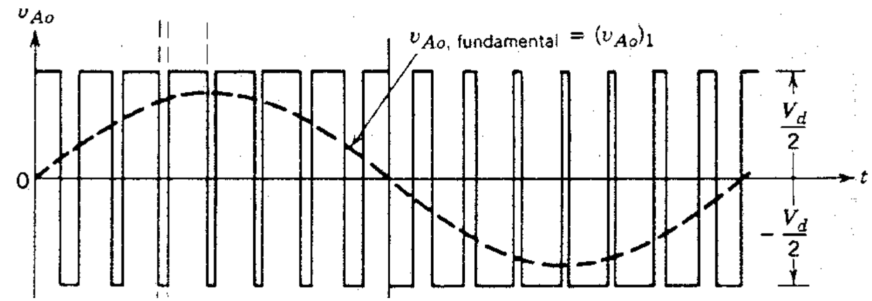
Amplitude modulation ratio: $m_a = \frac{\hat{V}_{control}}{\hat{V}_{tri}}$

Frequency modulation ratio: $m_f = \frac{f_s}{f_1}$



Details of a Switching Time Period





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

’Moving average’ of v_{A0} : $$V_{A0} = \frac{v_{control}}{\hat{V}_{tri}} \frac{V_d}{2} \quad with \quad v_{control} < \hat{V}_{tri} \qquad (1)$$

where: $$v_{control} = \hat{V}_{control} \sin \omega_1 t \qquad (2)$$

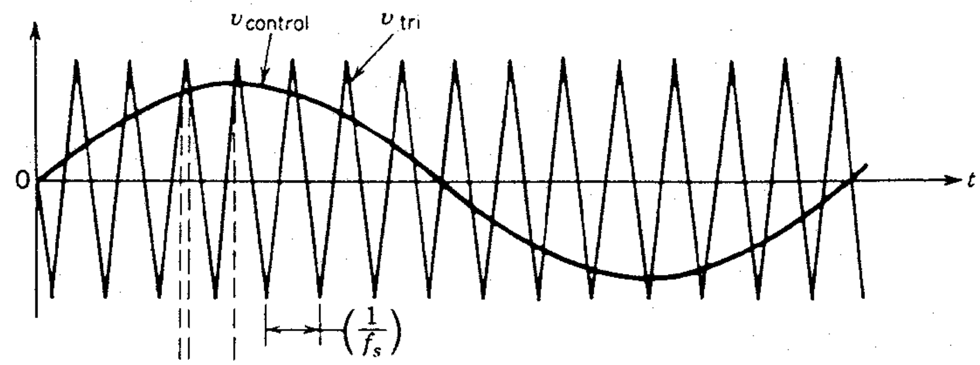
From (1) and (2): $$V_{A0,1} = \frac{\hat{V}_{control}}{\hat{V}_{tri}} \frac{V_d}{2} \sin \omega_1 t = m_a \frac{V_d}{2} \sin \omega_1 t$$

Modulation frequency

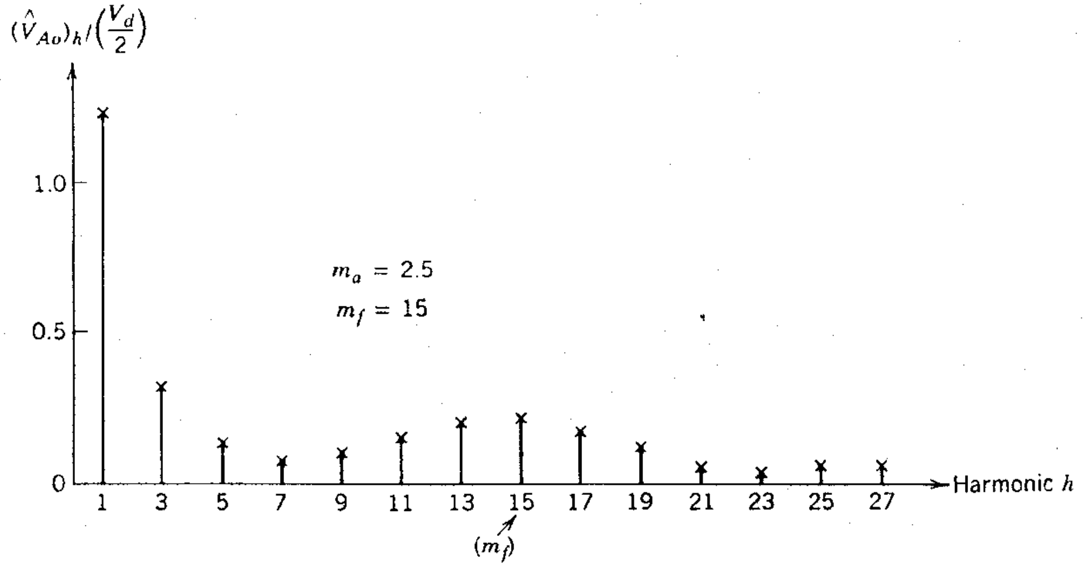
- Small m_f (m_f < 21)
  - Apply synchronous PWM to avoid subharmonics
  - Use methods to eliminate specific low order harmonics
- Large m_f (m_f > 21)
  - Good reproduction of reference wave
  - Side band harmonics are small
  - Switching harmonics can be eliminated with small filter

Overmodulation

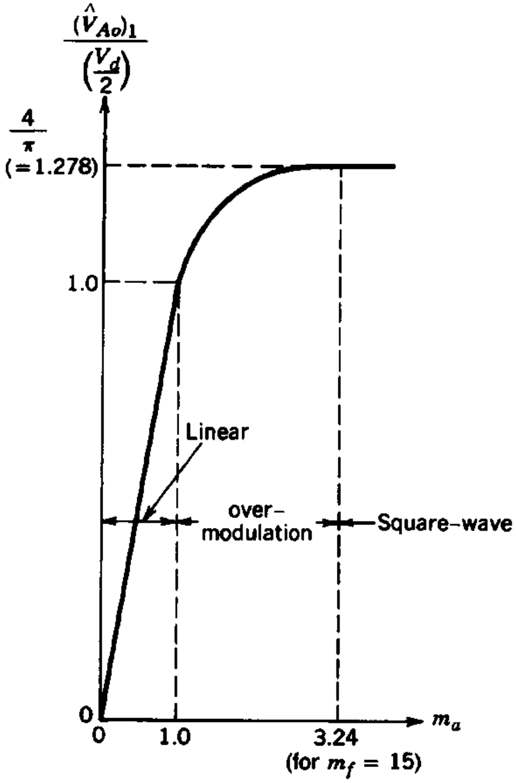
$$m_a > 1, \quad \hat{V}_{control} > \hat{V}_{tri}$$



Voltage spectrum:



- Output voltage Fundamental as a Function of m_a ;
- Shows the linear and the over-modulation region;
- square-wave operation in the limit



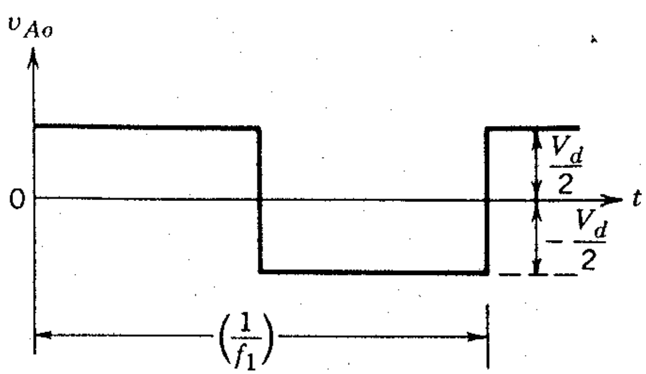
Overmodulation:

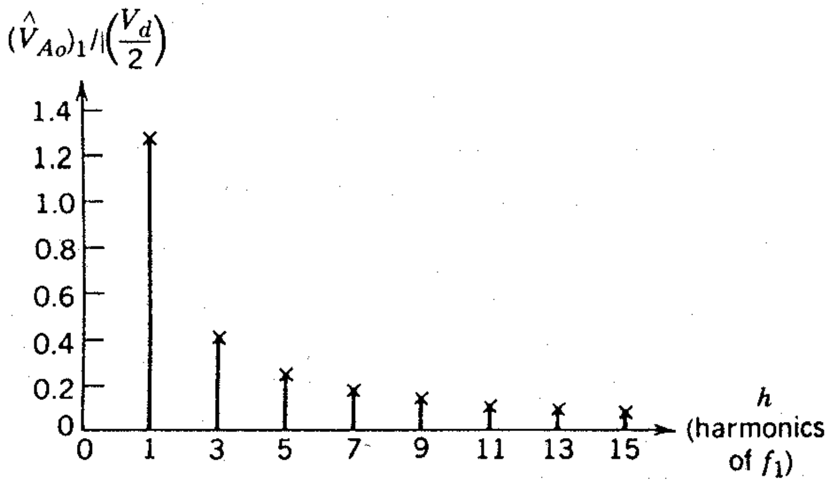
$$\frac{V_d}{2} < \left(\hat{V}_{A0}\right)_1 < \frac{4}{\pi}\frac{V_d}{2}$$

Square wave operation

$$\left(\hat{V}_{A0}\right)_{1,\max} = \frac{4}{\pi}\frac{V_d}{2} = 1.273\frac{V_d}{2}$$

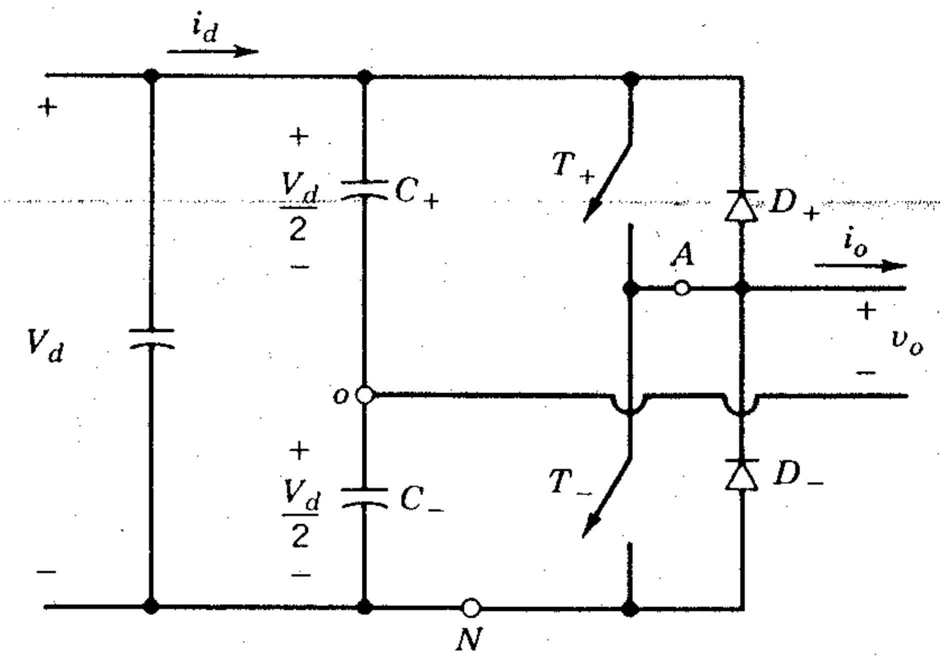
$$\left(\hat{V}_{A0}\right)_h = \frac{\left(\hat{V}_{A0}\right)_1}{h}$$



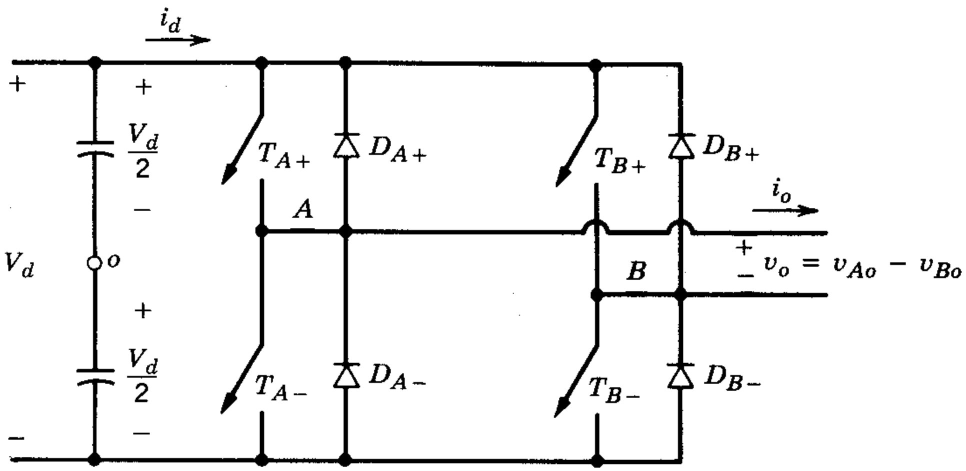


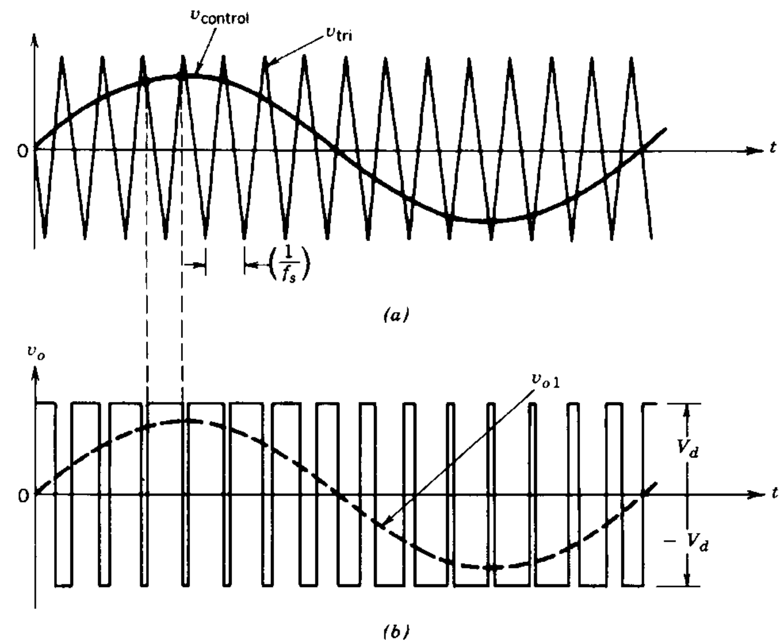
Single-phase inverters (half bridge)

- Current sharing between capacitors;
- i_0 cannot have a dc-component ➔ no transformer saturation problem;
- Switch utilisation:
  - $V_T = V_d$
  - $I_T = I_o$



Full-bridge converter





Preferred to half-bridge at high power levels

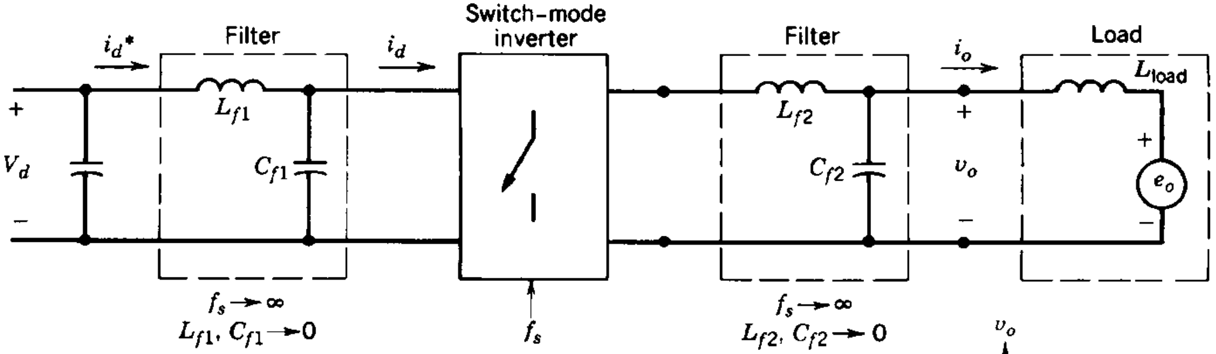
PWM with Bipolar voltage switching

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

$$\hat{V}_{0,1} = m_a V_d \qquad (m_a<1)$$

$$V_d < \hat{V}_{0,1} < \frac{4}{\pi} V_d \qquad (m_a>1)$$

DC-side current



(* = "averaged" currents)

f_s ➔ ∞ , so L and C ➔ 0

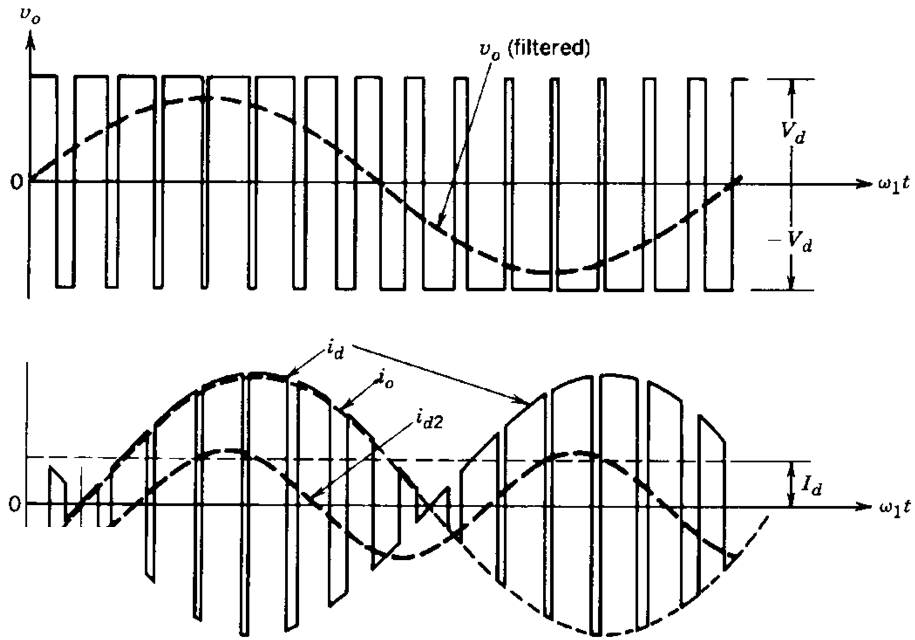
From power balance:

$$V_d\, i_d^*(t) = v_0(t)\, i_0(t)$$

$$= \sqrt{2}\, V_0 \sin \omega_1 t \cdot \sqrt{2}\, I_0 \sin(\omega_1 t - \phi)$$

$$= V_0 I_0 \cos\phi - V_0 I_0 \cos(2\omega_1 t - \phi)$$

$$i_d^*(t) = \frac{V_0 I_0}{V_d} \cos\phi - \frac{V_0 I_0}{V_d} \cos(2\omega_1 t - \phi)$$

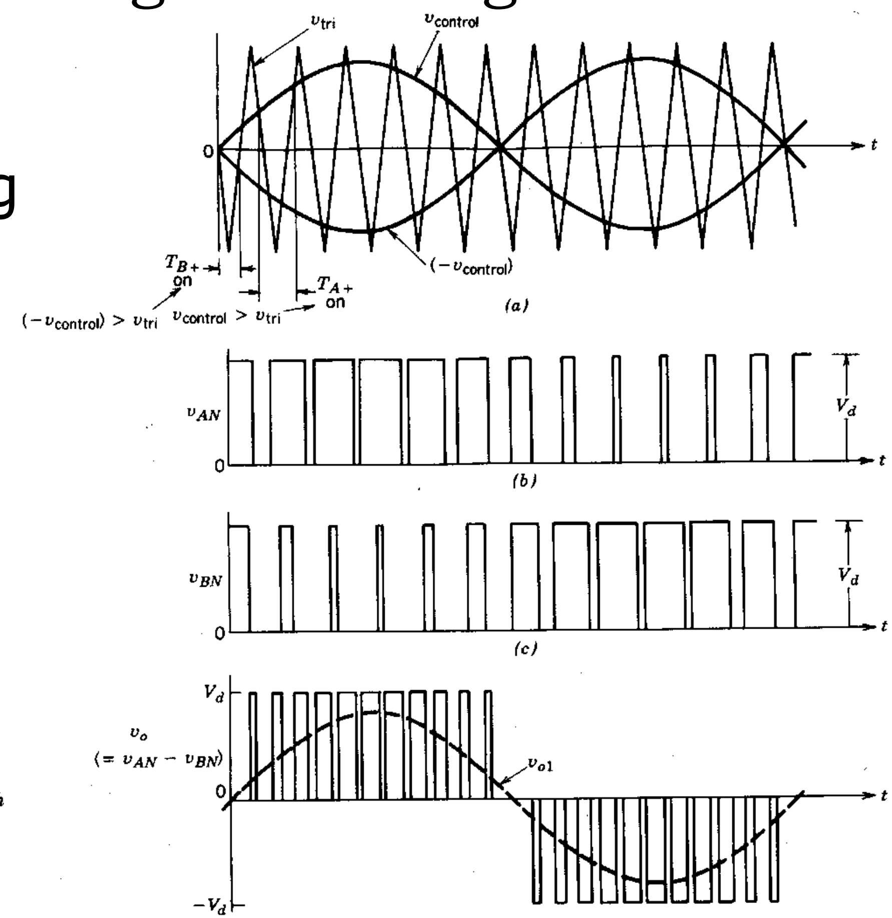


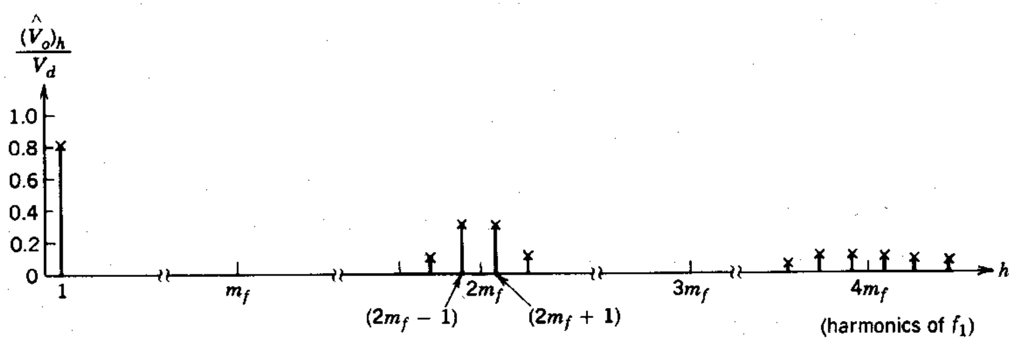
Input current:
- DC component
- LF component of double fundamental frequency
- Strong HF components (steep slopes)

Full-bridge converter –

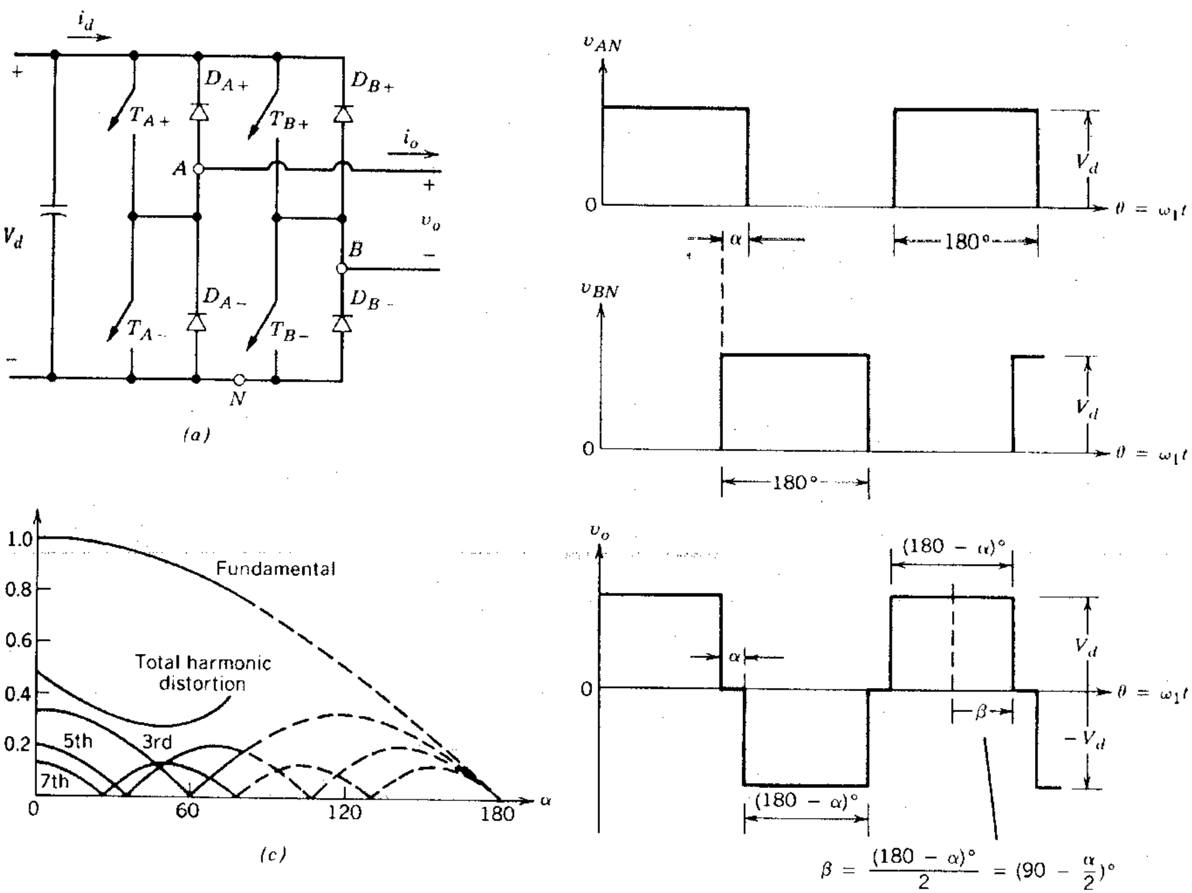
PWM with unipolar voltage switching

- Double control voltage
- Same output voltage and magnitude as bipolar switching
- Lower ripple current (about 50%)
- Less harmonics





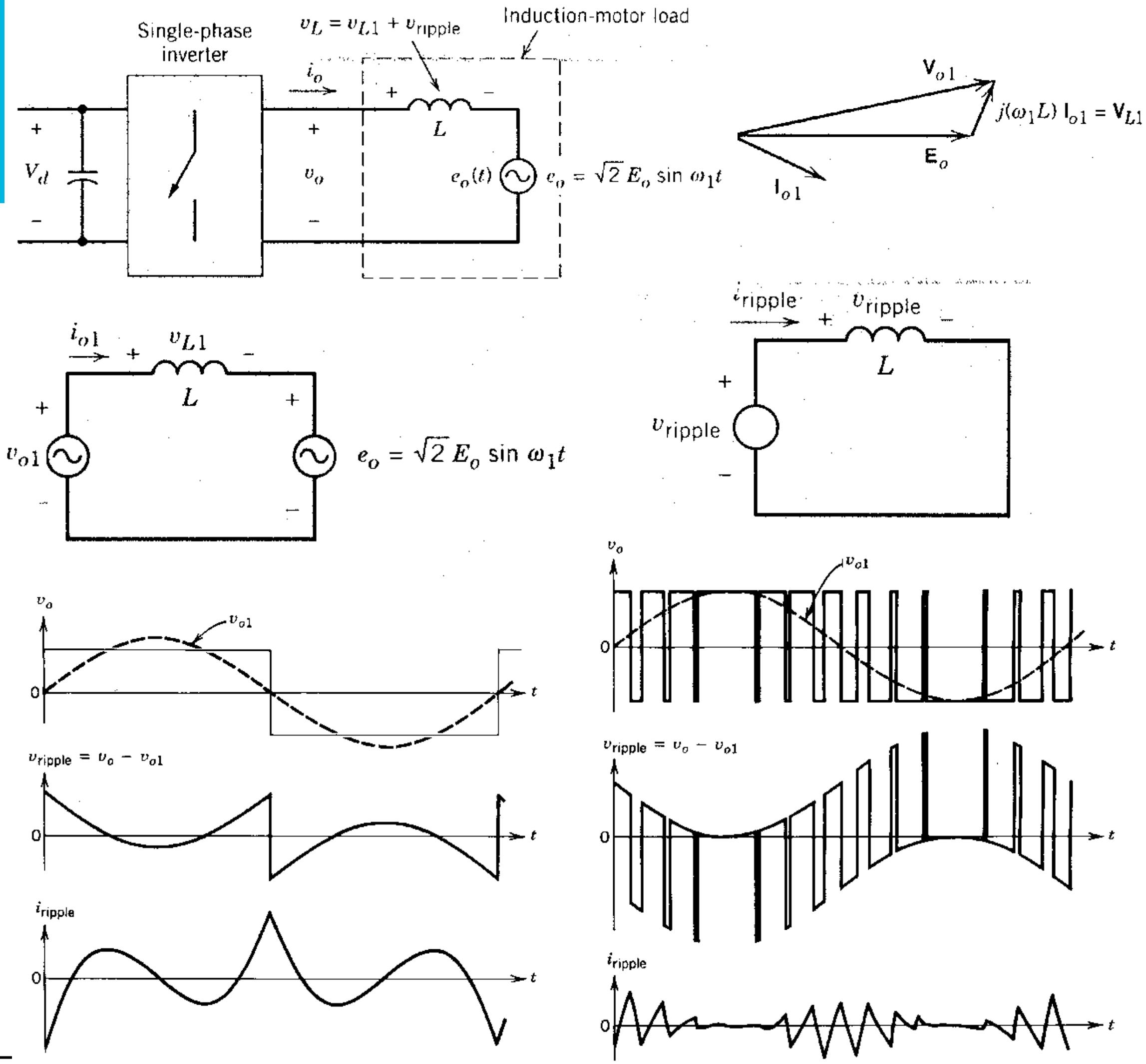
Square wave operation – output voltage control



$$(\hat{V}_0)_h = \frac{2}{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} v_0 \cos(h\theta)\ d\theta$$

$$= \frac{4}{\pi h} V_d \ \sin(h\beta)$$

Voltage and current ripple



Apply superposition:

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

$$i_0(t) = i_{01}(t) + i_{ripple}(t)$$

Fundamental (phasors):

$$\mathbf{V}_{01} = \mathbf{E}_{01} + j\omega_1 L \mathbf{I}_{01}$$

Ripple current:

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

(b): largest ripple during zero crossing of voltage

Square-wave

PWM bipolar

Switch utilisation ratio (SUR)

$$SUR = \frac{total\ apparent\ converter\ power\ S}{q\, V_T \cdot I_T}$$

q = total number of switches

Example:
Full bridge square-wave with sinusoidal current and output current I_0

$$SUR = \frac{P_0}{\sum_{switches} P_T}$$

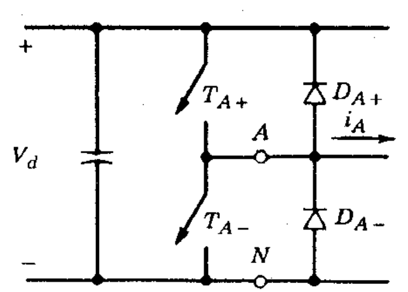
Output: $V_{01,\max} = \frac{4}{\pi\sqrt{2}} V_{d,\max}$; I_0

Switch T: $V_T = V_{d,\max}$; $I_T = \sqrt{2}\ I_{0,\max}$

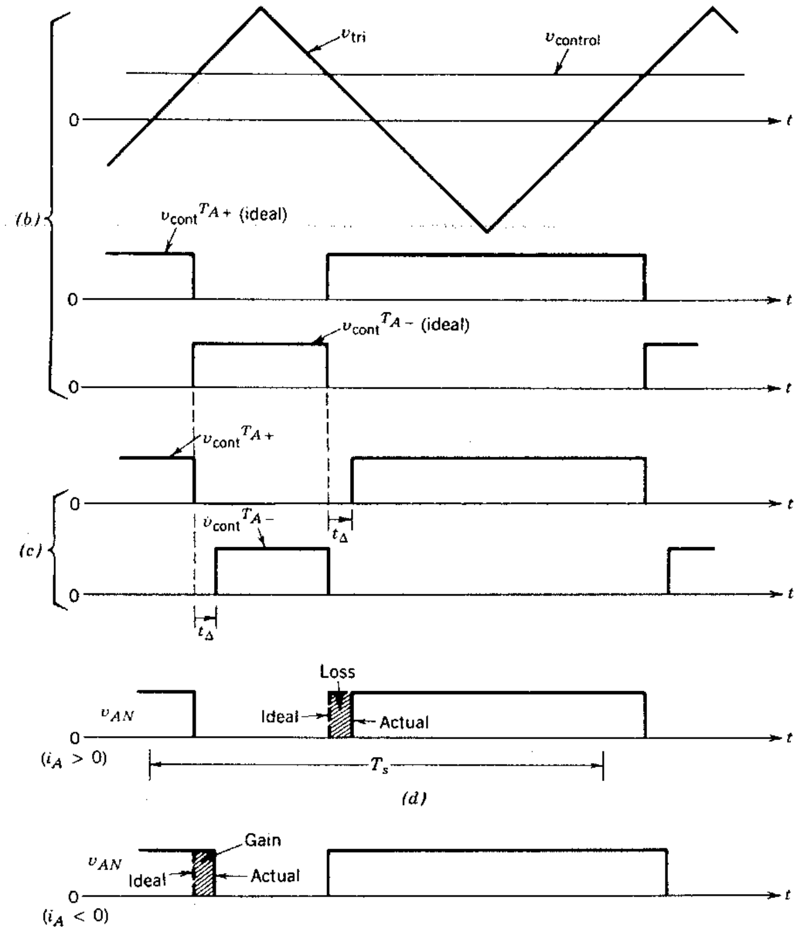
$$SUR = \frac{P_0}{q\, P_T} = \frac{V_{01,\max} \cdot I_{0,\max}}{q\, V_{d,\max} \cdot \sqrt{2}\, I_{0,\max}} = \frac{\frac{4}{\pi\sqrt{2}} V_{d,\max} \cdot I_{0,\max}}{4\ V_{d,\max} \cdot \sqrt{2}\, I_{0,\max}} = \frac{1}{2\pi}$$

Effect of blanking time

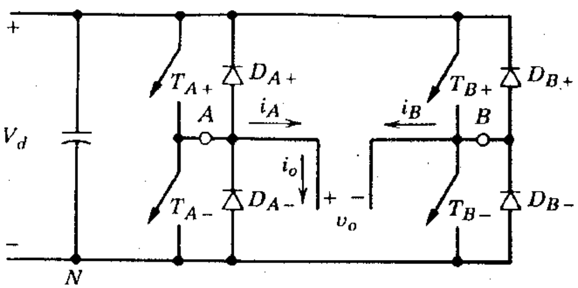
- Blanking time (dead time) t_Δ to avoid shoot-through

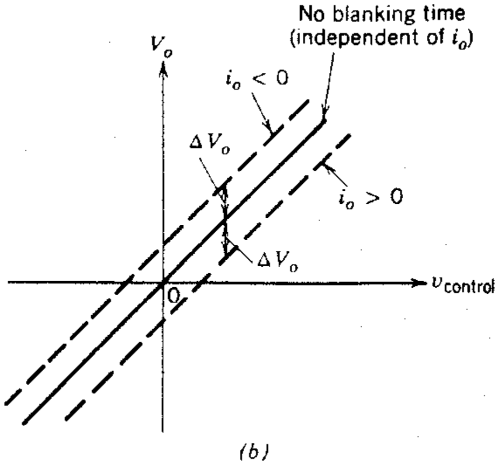


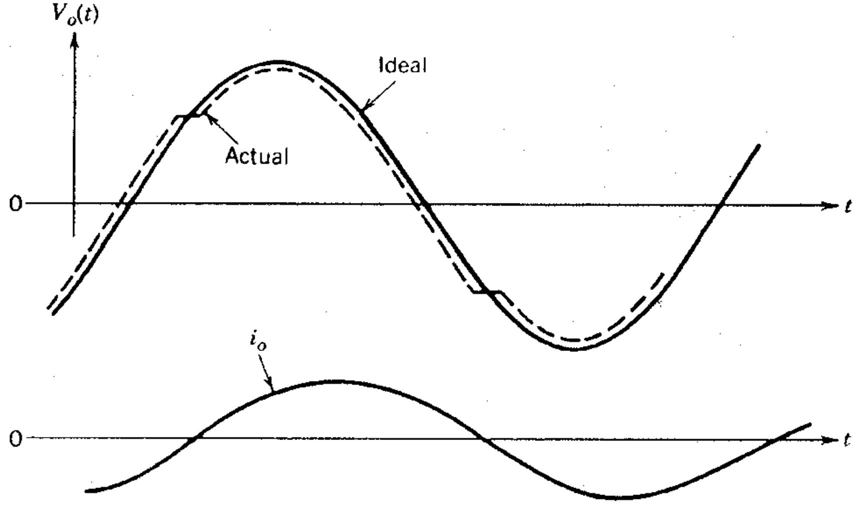
$$\Delta V_{AN} = \begin{cases} +\dfrac{t_\Delta}{T_s} V_d & (i_A > 0) \\ -\dfrac{t_\Delta}{T_s} V_d & (i_A < 0) \end{cases}$$



Effect of blanking time (2)





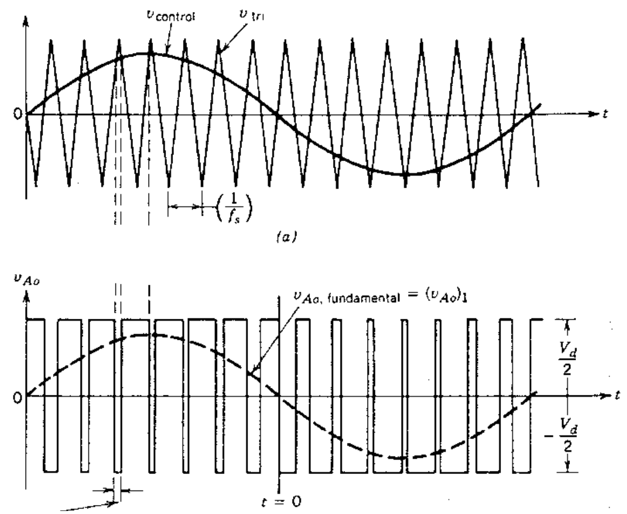


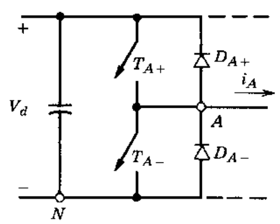
$$\Delta V_{AB} = \Delta V_{AN} - \Delta V_{BN}$$

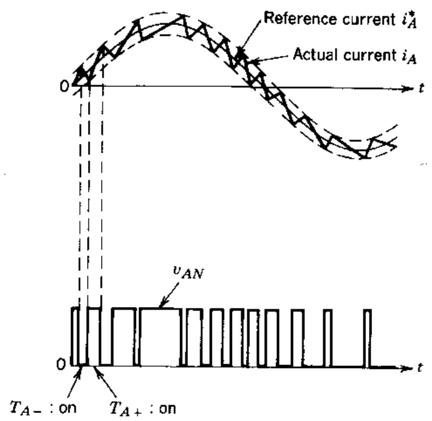
$$\Delta V_{AB} = \begin{cases} +\dfrac{2\,t_\Delta}{T_s} V_d & (i_0 > 0) \\ -\dfrac{2\,t_\Delta}{T_s} V_d & (i_0 < 0) \end{cases}$$

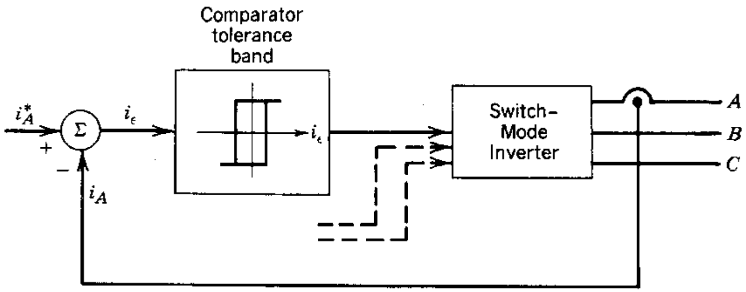
Voltage versus Current Source

- 1) VSI with unipolar or bipolar modulation
  - Behaves as voltage source
- 2a) Current mode modulation:
  - VSI with hysteresis modulation
  - Behaves as current source
  - Variable switching frequency
  - Constant current ripple amplitude



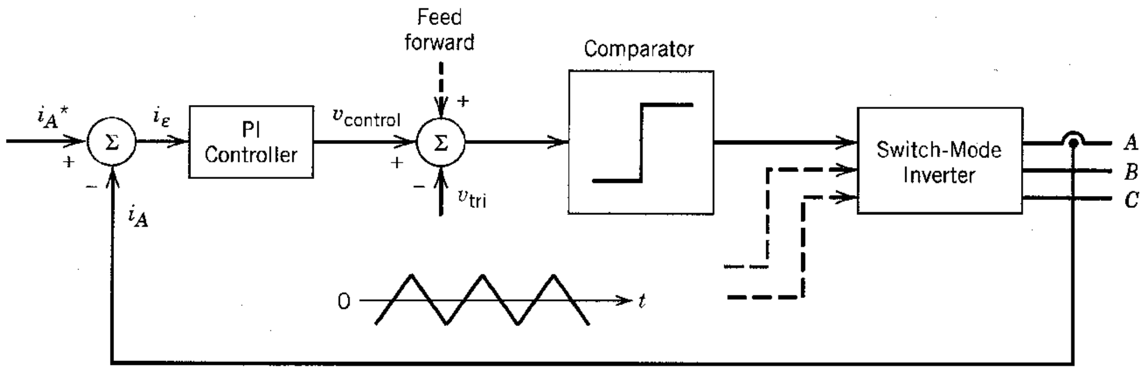






Voltage versus Current Source (2)

- 2b) VSI with Fixed frequency current control (triangular modulation with feedback)

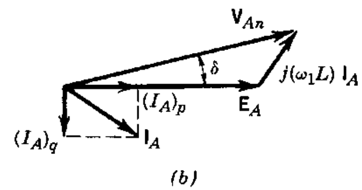


Rectifier mode operation

- Phasor representation for fundamental:

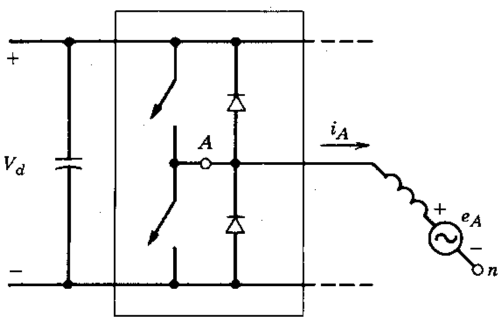
$$\mathbf{V}_{An} = \mathbf{E}_A + \mathbf{V}_L \quad \text{where} \quad \mathbf{V}_L = j\omega L_s \mathbf{I}_s \qquad \mathbf{I}_A = \frac{\mathbf{V}_{An} - \mathbf{E}_A}{j\omega L_s}$$

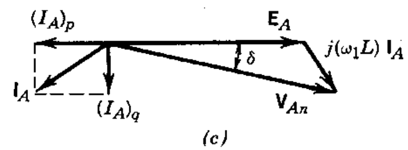
- The phase and amplitude of $v_{An}(t)$ can be set through the input signal $v_{control}$ of the modulator

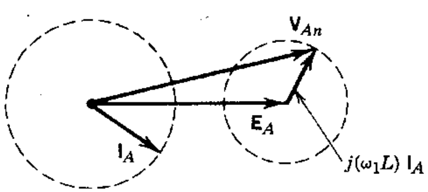


$$v_L = L_s \frac{di_s}{dt}$$

$$v_L = L_s \frac{di_s}{dt}$$







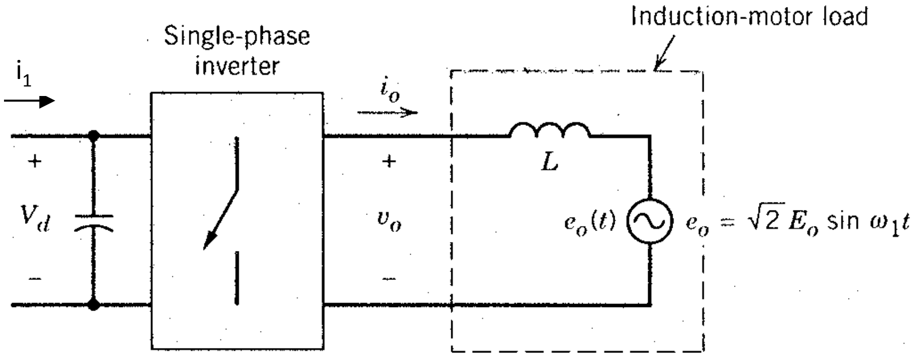


Figure 2

Figure 2 shows a single-phase inverter connected to a single phase induction motor with counter emf e_0.

The output voltage v_0 of the inverter is obtained by bipolar voltage switching modulation scheme. To obtain a low distortion linear modulation is applied (no overmodulation; $m_a<1$).

Given is further:

$V_d = 350V$	(DC link voltage)
ω_1	(fundamental frequency of v_o and e_0)
$\omega_{1,nom} = 2\pi 50$ rad/s	(nominal value of ω_1)
$V_{01,nom} = 230$ V	(nominal rms value of fundamental of v_0)
e_0	(counter emf)
$L = 30$ mH	(inductance of machine)
$f_s = 7.5$ kHz	(switching frequency)

At nominal speed and nominal voltage the input power of the loaded drive is 2kW at $\cos\phi_1=0.8$.

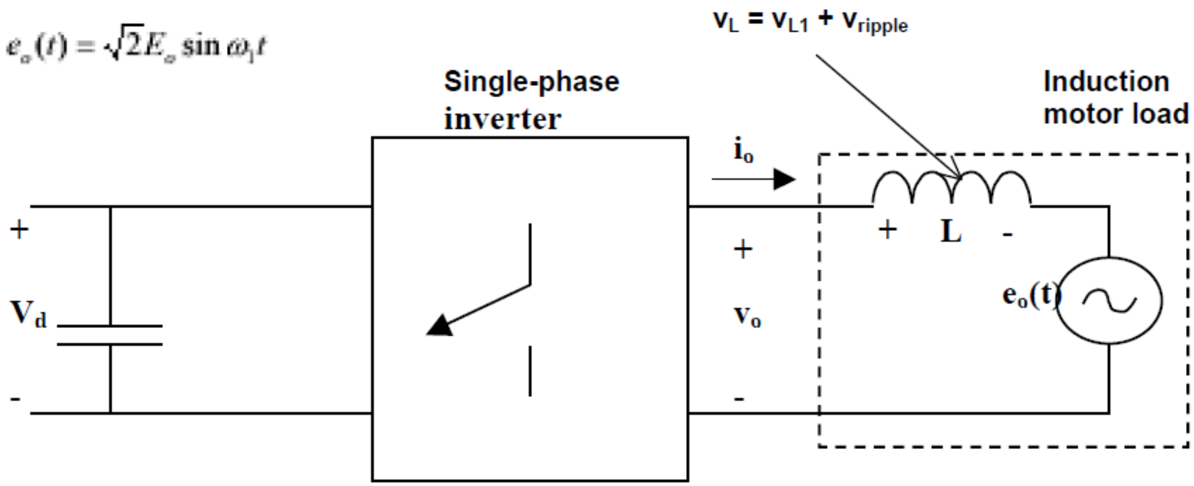
(a) Draw the relevant circuit time diagrams to show the operation of the inverter. Indicate which switch is on at what time period. Sketch equivalent circuit models to calculate the fundamental component of the current i_o and the ripple component of the current i_o. Calculate the maximum value of the peak-to-peak current ripple in i_o that is caused by the switching.

(b) Calculate the rms value of the fundamental of i_o when the machine runs at rated speed and rated power. Sketch a phasor diagram with the phasors of e_0, v_0 and i_0.

(c) Calculate the modulation ratio m_a such that the machine runs at nominal speed and nominal voltage.

(d) What will change in the answers to problems b) and c) if unipolar switching is used instead of bipolar switching?

(e) Calculate the low-frequency (<1 kHz) peak-to-peak voltage ripple ΔVd assuming that the current i1 is constant and C=1mF.



Given is a single-phase full bridge inverter operating in a square-wave mode. The dc-voltage is 244V and the frequency of the output voltage that supplies a motor load is 47Hz. The inductance is L = 100 mH. Calculate the peak value of the ripple in the output current.

Image credits

- All uncredited diagrams are from the book "Power Electronics: Converters, Applications, and Design" by N. Mohan, T.M. Undeland and W.P. Robbins.
- All other uncredited images are from research done at the EWI faculty.