TSTE25 Power Electronics

Lecture 2

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Outline

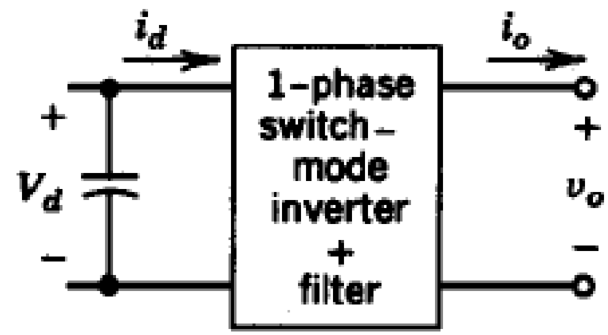
- DC-AC switching inverters
  - Switch-mode principle
  - Single-phase inverter
    - Half-bridge
    - Full-bridge
  - PWM switching
  - Full-bridge DC/DC converter

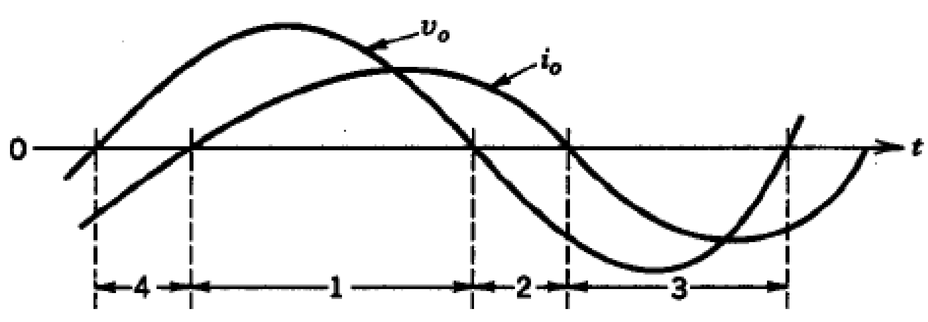
Switch-mode dc-ac inverter

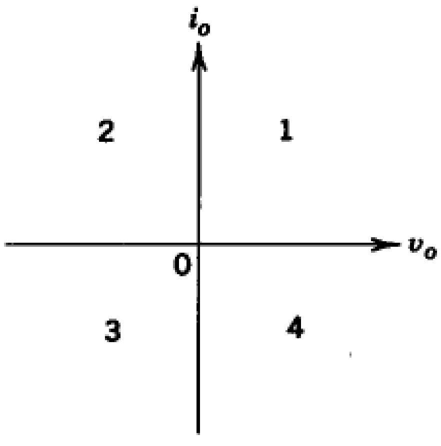
- Sinusoidal ac
- Controlled magnitude
- Controlled frequency
- Common use
  - Ac motor drive
  - Uninterruptable ac power supply
  - 12V DC -> 230V AC inverter

Switch-Mode DC-AC Inverter

- Fixed dc-voltage
- Switched output filtered to generate sinusoidal v_o
- Assume inductive load at v_o, i_o lagging
- Waveforms in all four quadrants



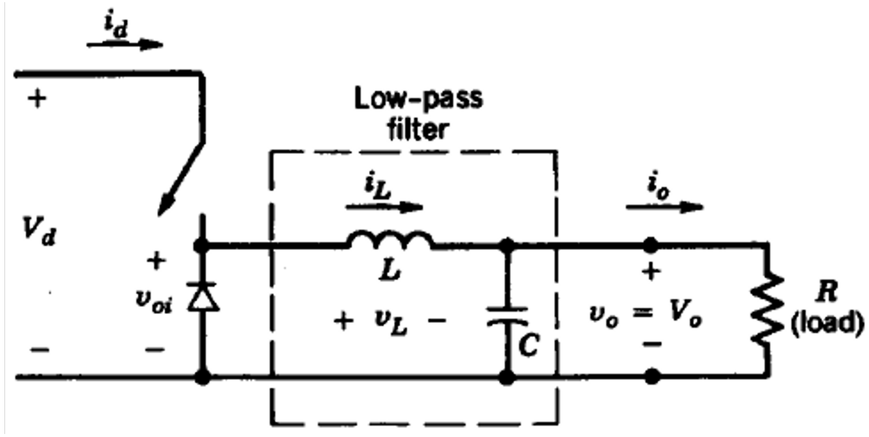


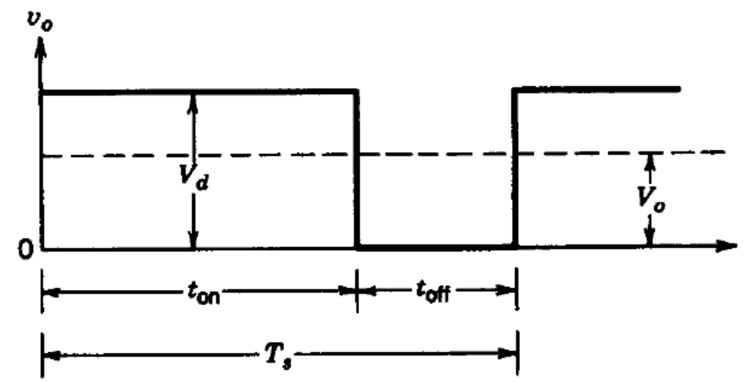


Compare: Step-down (buck) converter

- Output voltage amplitude controlled by switch duty cycle

$$\frac{V_o}{V_d} = D$$



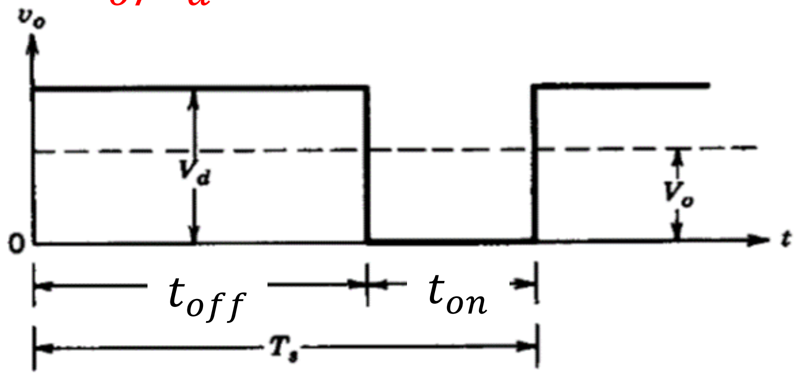


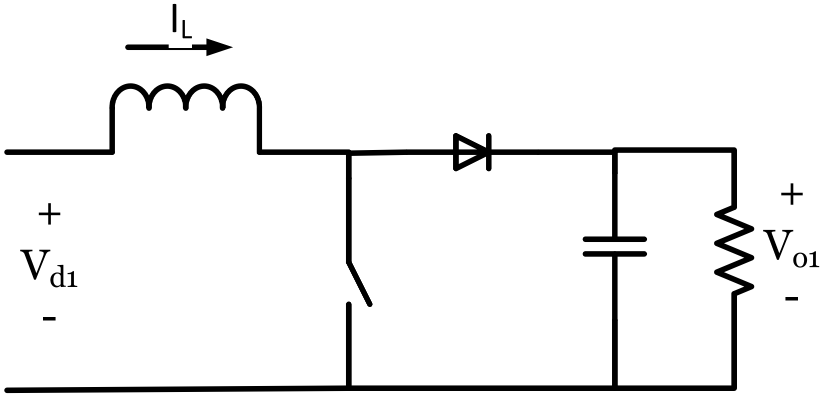
Compare: Step-up (boost) converter

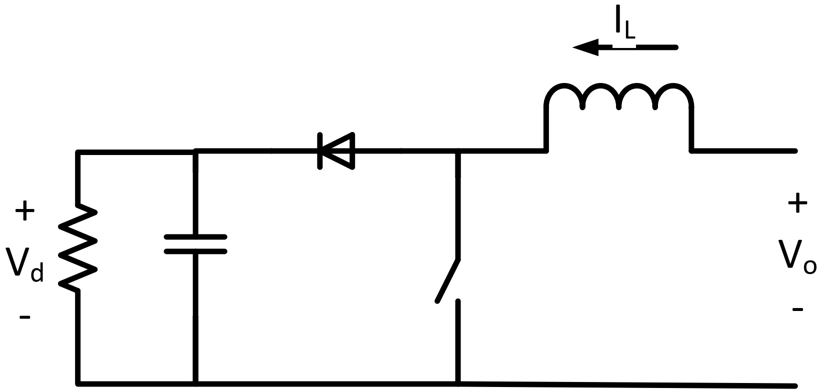
- Voltage ratio defined by duty cycle

$$V_{o1}/V_{d1} = \frac{1}{1-D}$$

- Current from low voltage side to high voltage side
- Inverted Boost converter
  $V_o = V_{d1}, V_d = V_{o1}$
  $V_o/V_d = 1 - D$

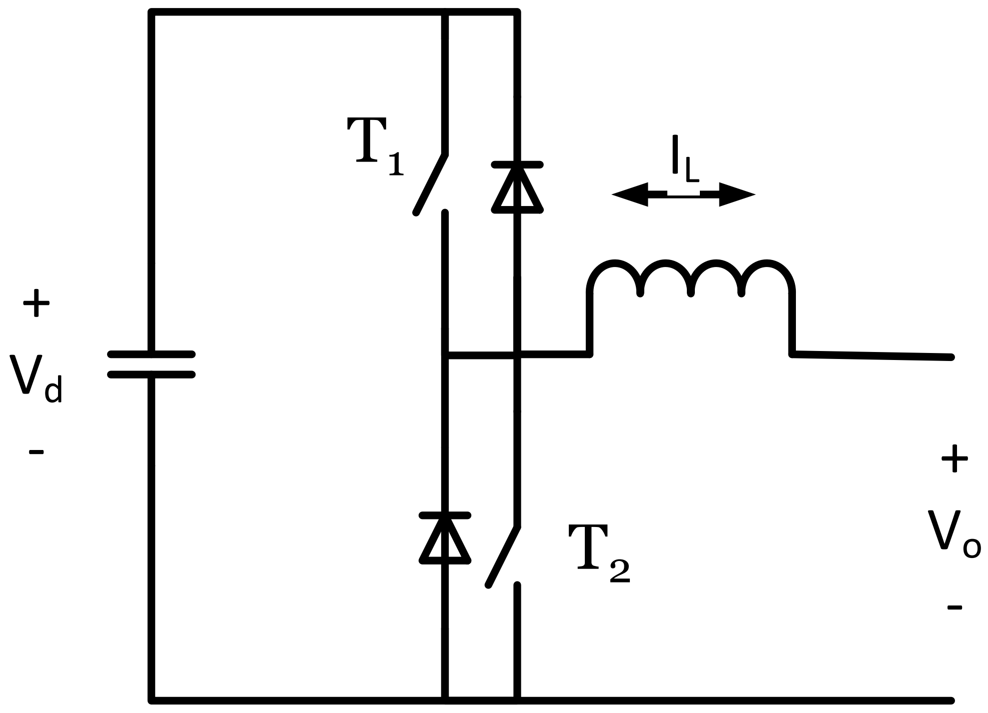


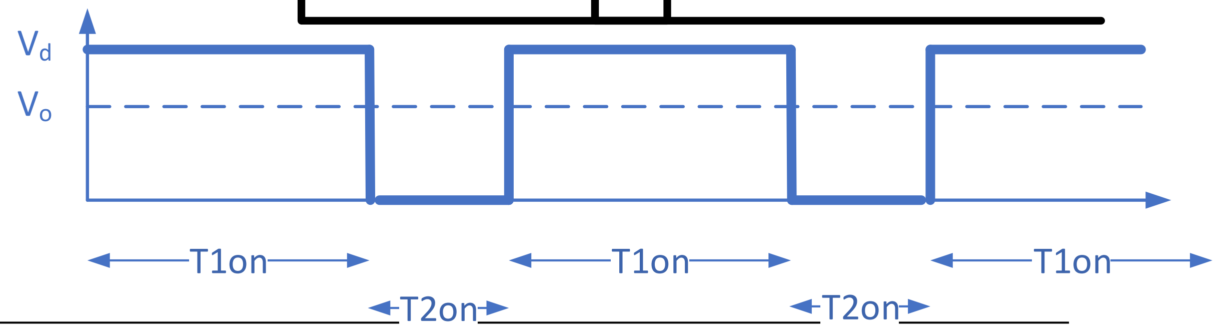




Half-bridge(2-level) DC/DC converter

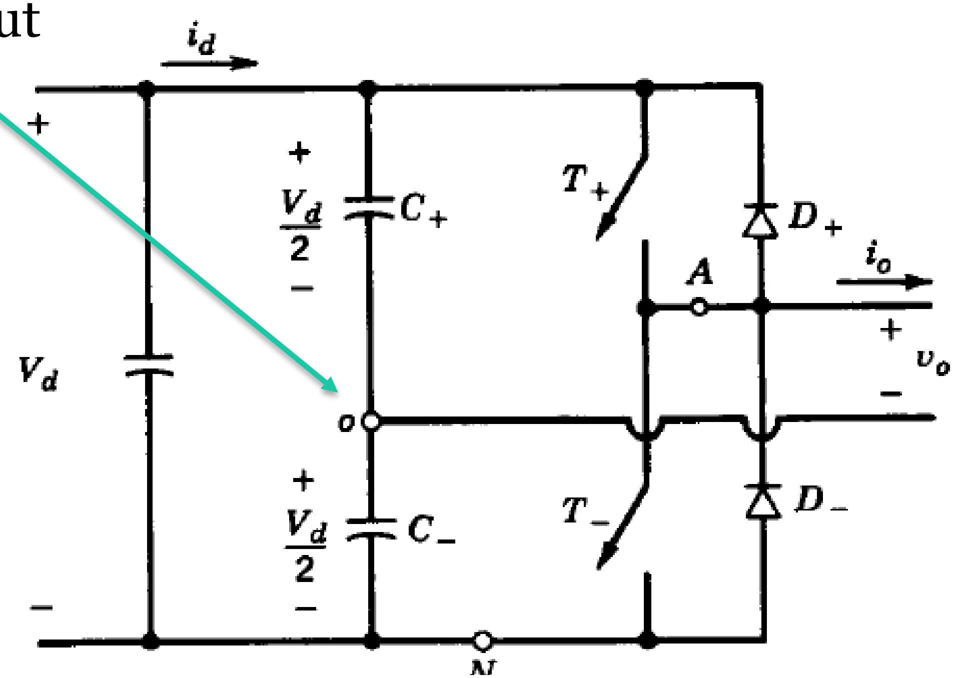
- 2 output voltage levels
  - (V_d, 0)
- Average voltage magnitude controlled by duty cycle
  - $V_o/V_d = D(T_1)$
  - $D(T_2) = 1 - D(T_1)$
- Bi-directional current
- Forbidden state:
  - T_1 and T_2 both on
  - Short **circuit**

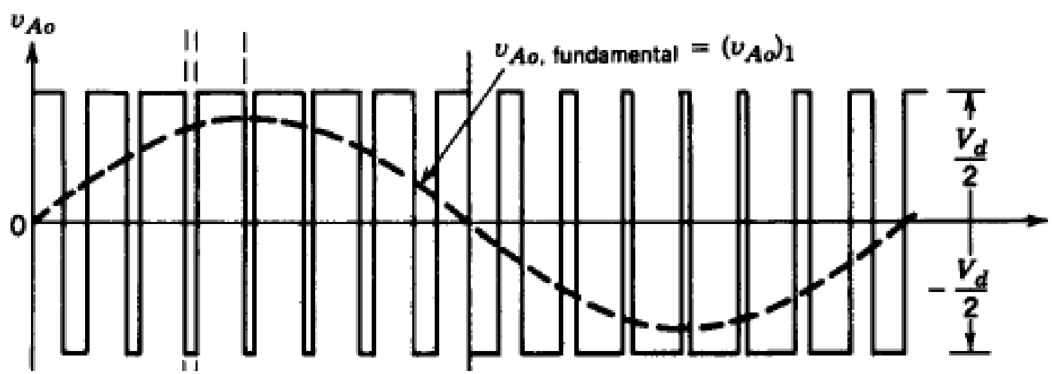




Half-bridge (2-level) DC/AC converter

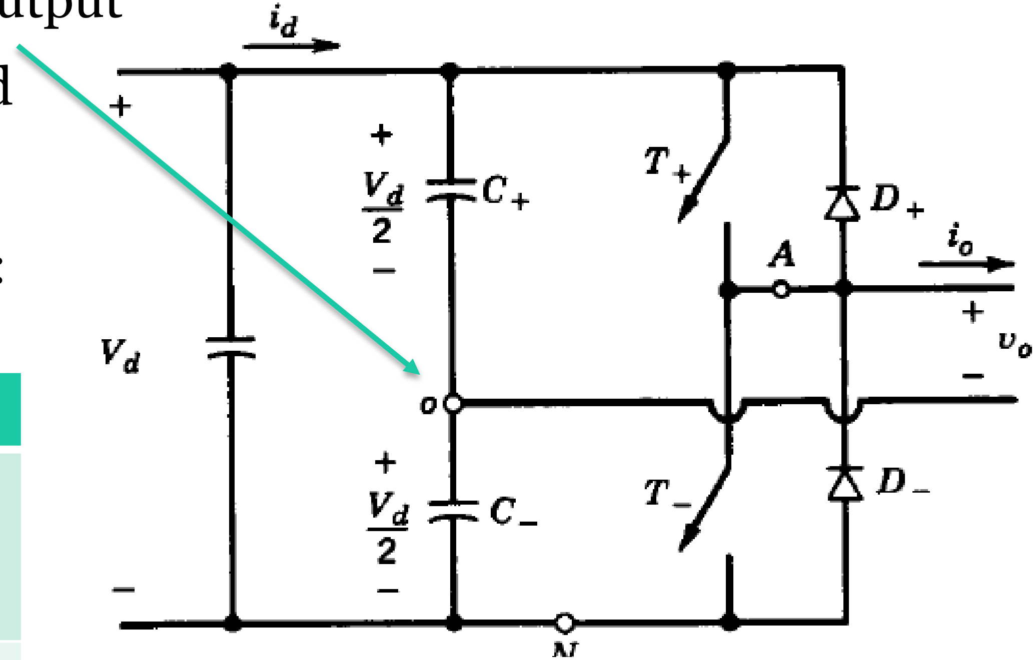
- DC-side midpoint 'o'
  reference point for ac-output
- Output voltage, v_{A0}, switched between $+\frac{V_d}{2}$ and $-\frac{V_d}{2}$
- Sinusodial variation of D
  - Ac output voltage



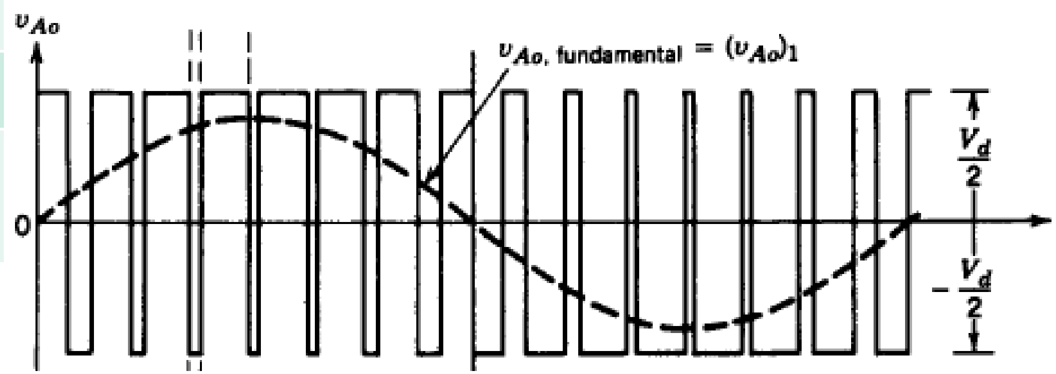


Half-bridge (2-level) converter

- DC-side midpoint 'o'
  reference point for ac-output
- Output voltage switched between $+\frac{V_d}{2}$ and $-\frac{V_d}{2}$
- 4 possible switch states:



T+	T-	
Off	Off	V_o-o def by i_o. $i_o>0$: v_o-o = $-V_d/2$ $i_o<0$: v_o-o = $+V_d/2$
On	Off	v_o-o = $+V_d/2$
Off	**On**	v_o-o = $-V_d/2$
On	**On**	Short circuit. Forbidden state



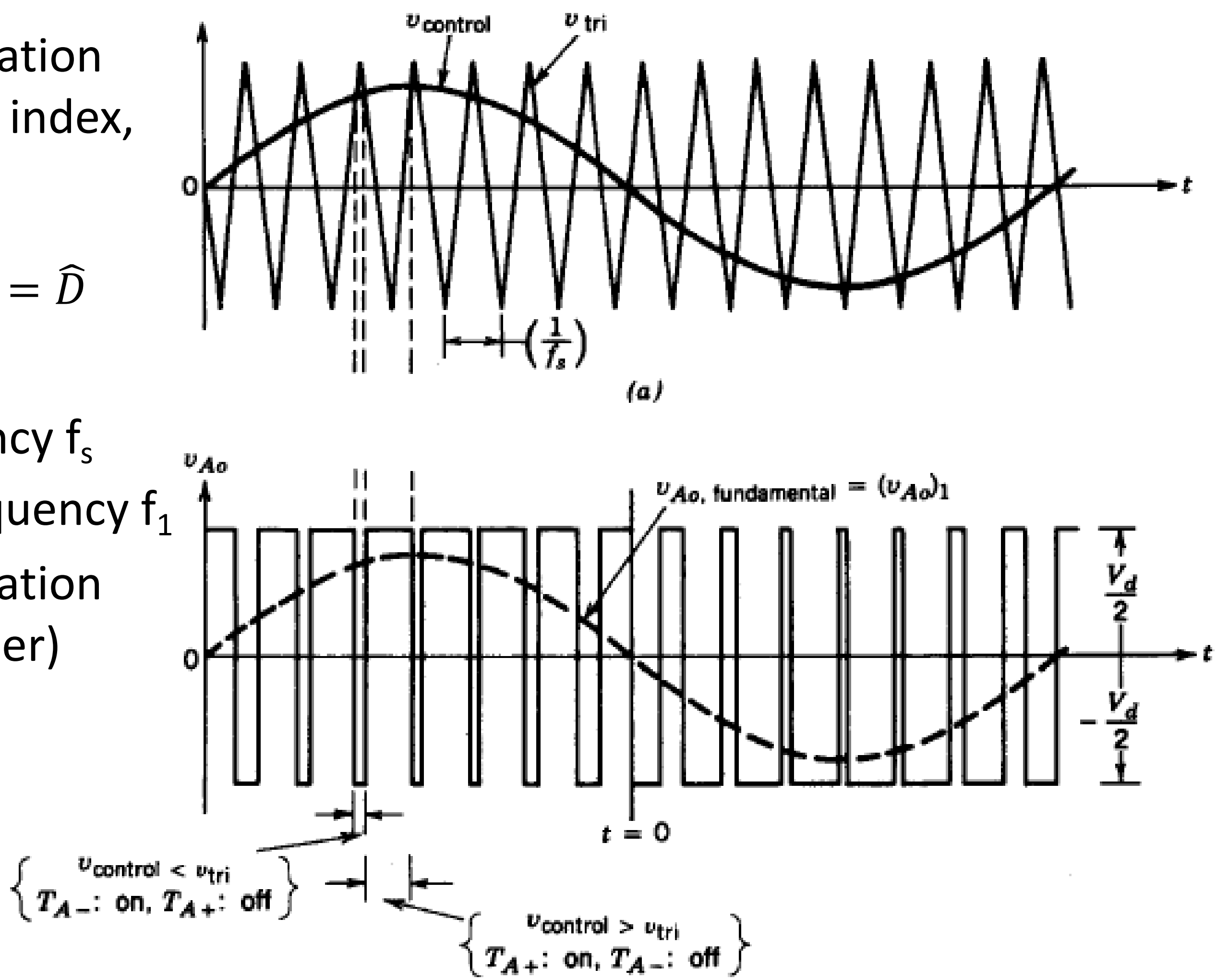
Pulse-width modulated switching scheme

- Amplitude modulation ratio (modulation index, peak duty cycle)

$$m_a = \frac{\hat{V}_{A01}}{V_d/2} = \frac{\hat{V}_{control}}{\hat{V}_{tri}} = \hat{D}$$

- Switching frequency f_s
- Fundamental frequency f_1
- Frequency modulation ratio (pulse number)

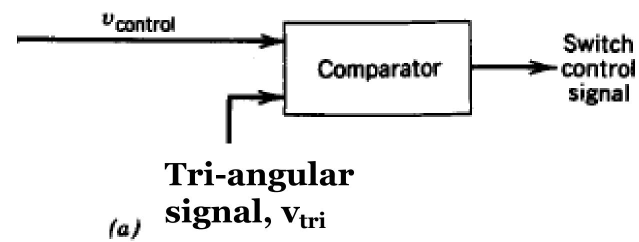
$$m_f = \frac{f_s}{f_1}$$

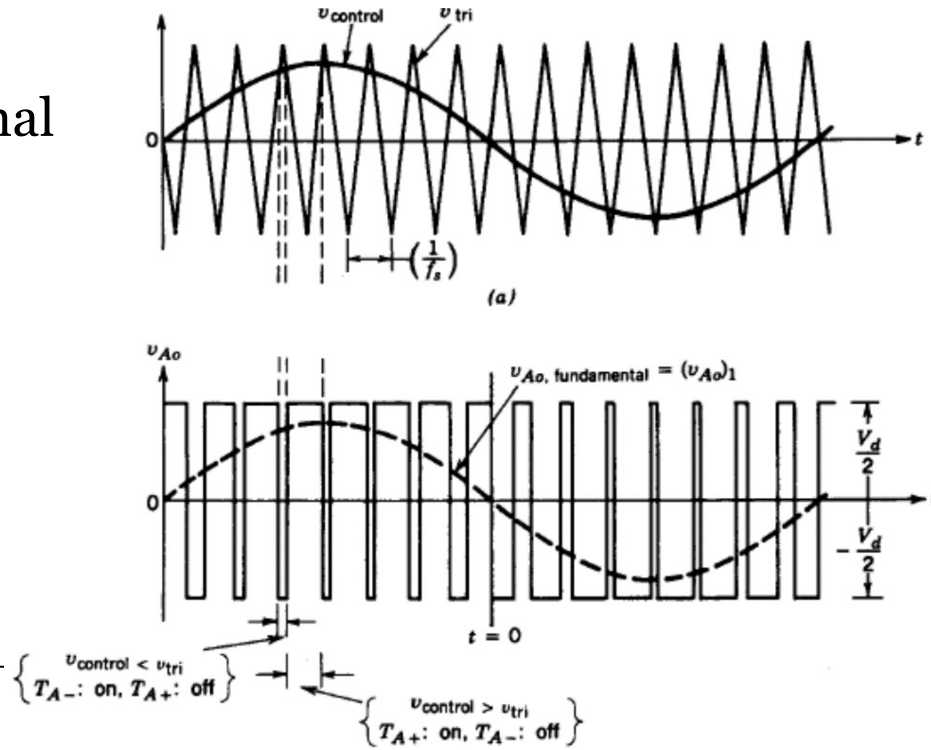


DC/AC-converter control

- Pulse width modulation, PWM, to control switching
- Switching frequency, f_{s}, the repetition rate of turn-on/off
  - v_{tri}, triangular signal between -1 and +1
- Reference signal, $v_{control} = m_a \sin \omega_1 t$
  - $0 < m_a < 1$
- Output voltage:

$$V_{A0} = m_a \frac{V_d}{2} \sin \omega_1 t$$

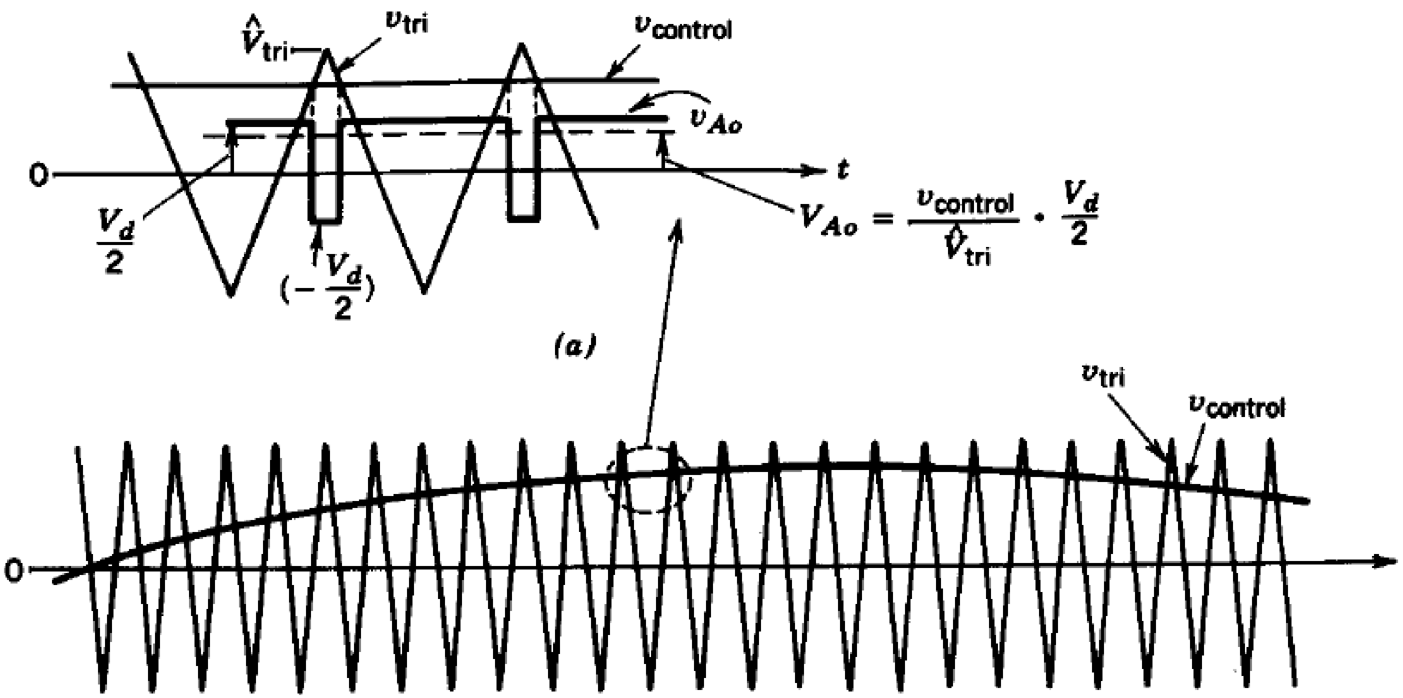




PWM modulation control

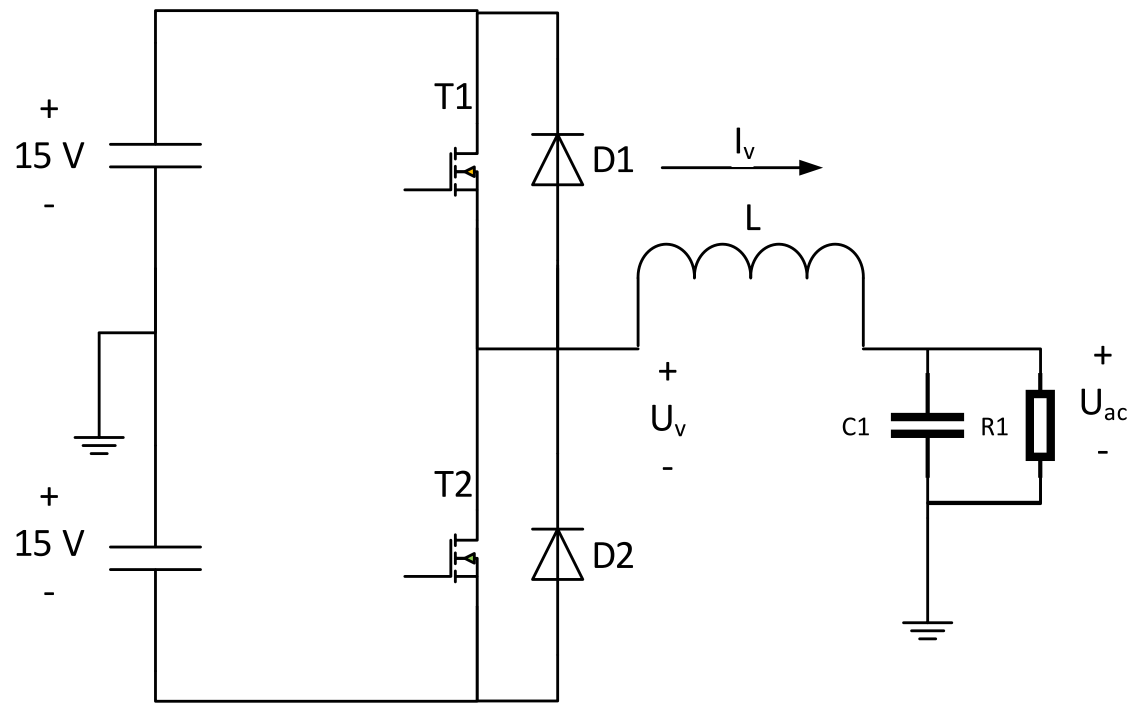
- Fundamental frequency output, $\hat{V}_{ao1} \sin \omega_1 t$
- 0 < m_a < 1, linear range

$$\hat{V}_{ao1} = m_a \frac{V_d}{2}$$

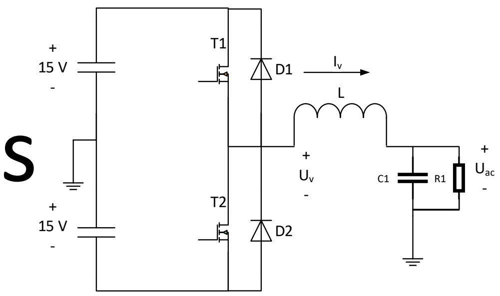


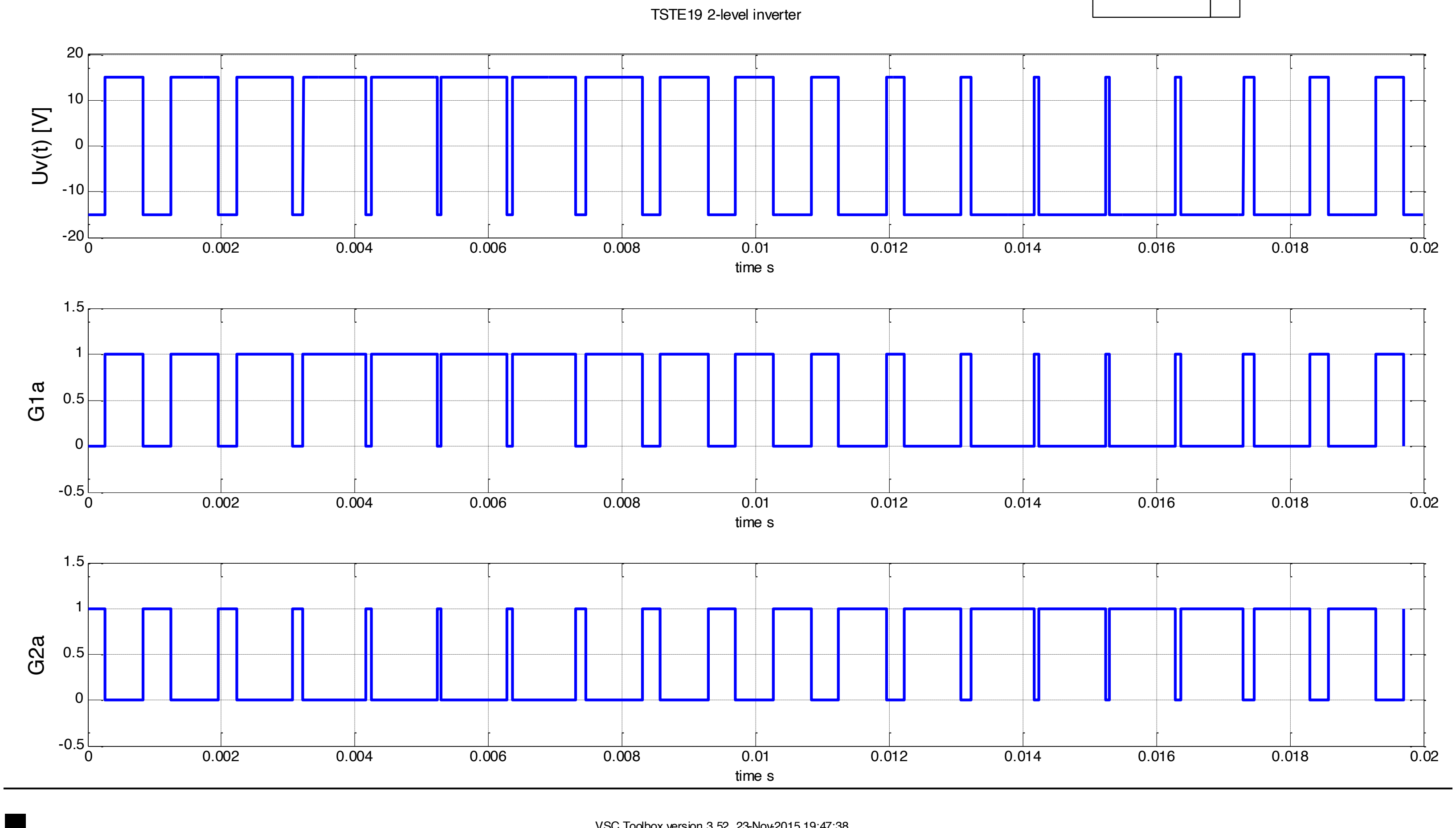
Half-bridge converter example

- Total dc-voltage, positive-to-negative side
  - $U_d = 30V$
- DC-voltage positive and negative side to ground
  - $\frac{U_d}{2} = \pm 15V$

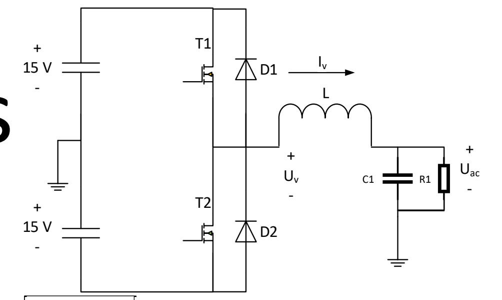


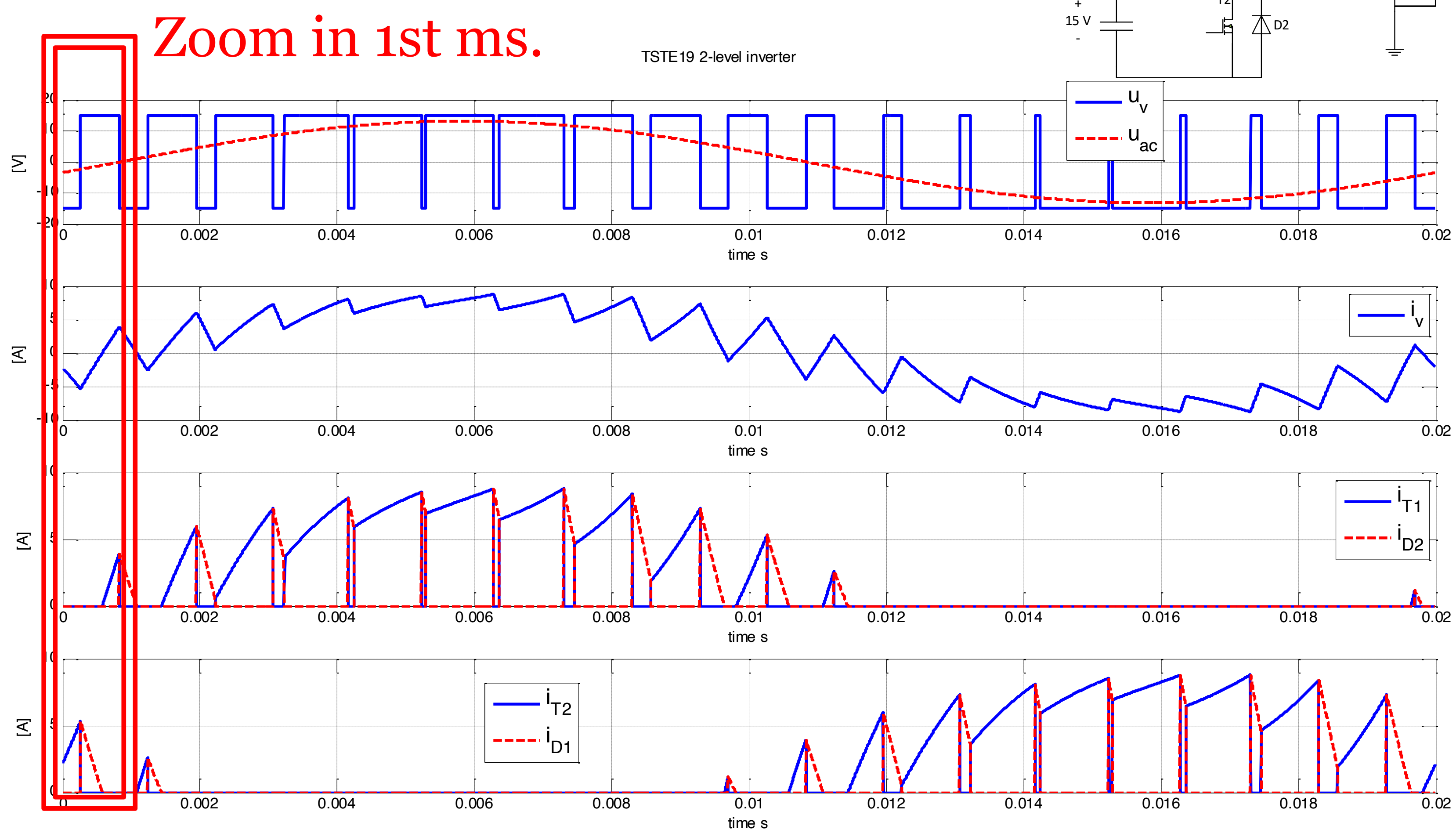
Output voltage & gate signals





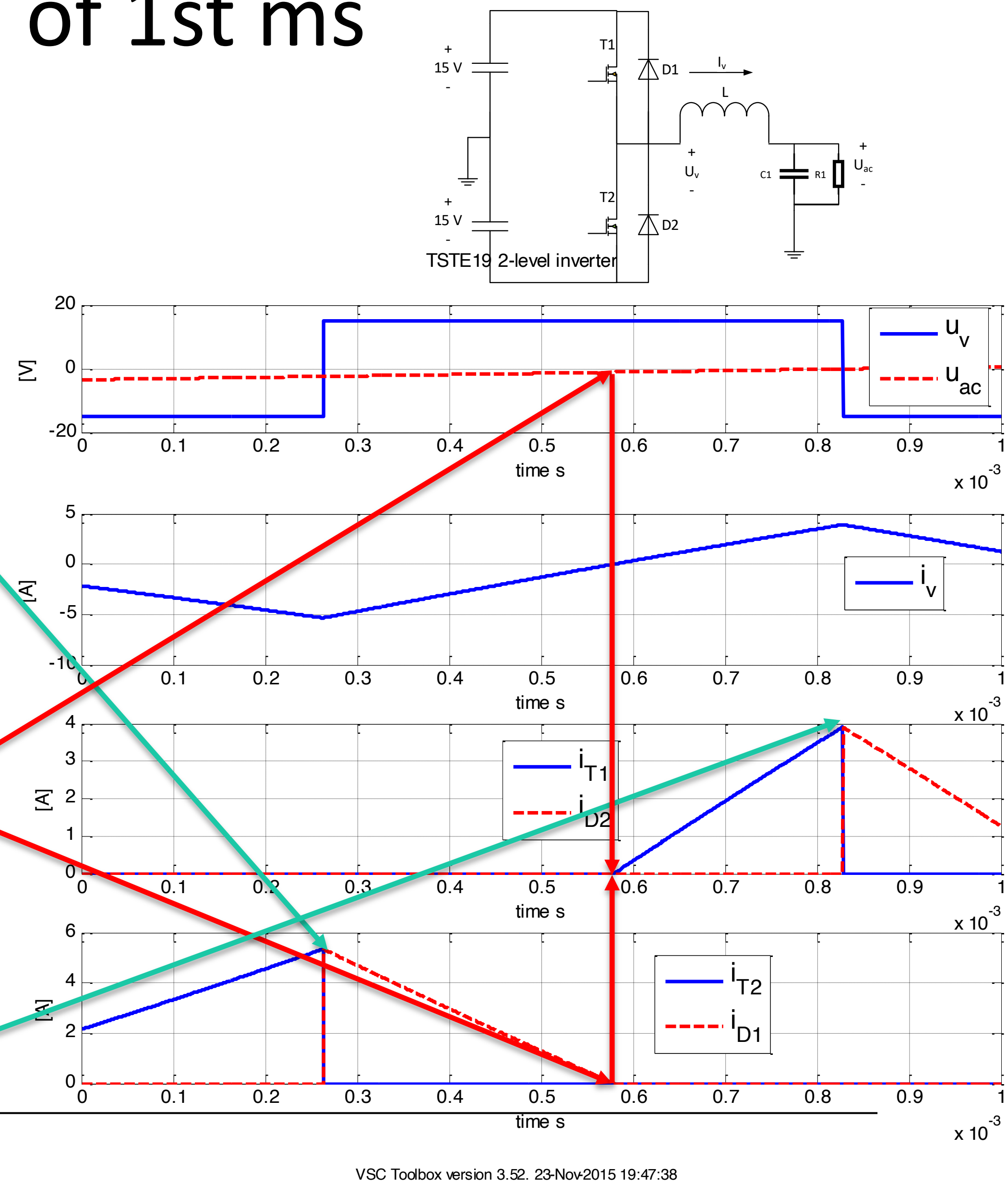
Voltage & current waveforms





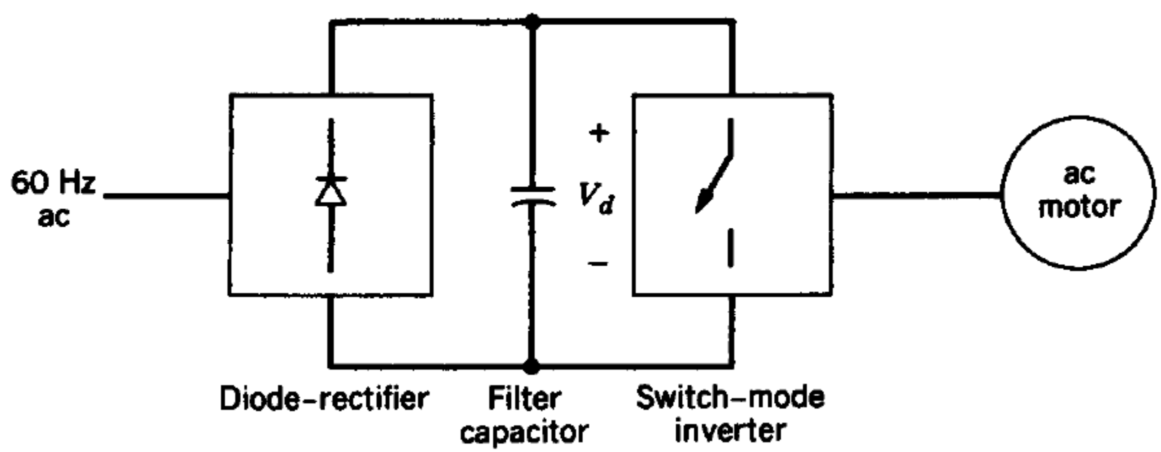
Zoom in of 1st ms

- $t<0.27$ ms,
  - T2 on
  - $i_v < 0$
- $t=0.27$ ms,
  - G2 off, G1 on
  - $i_v < 0$
    T2 to D1 commutation
- $t=0.57$ ms
  - $i_v > 0$
    D1 to T1 conducting
- $t=0.83$ ms
  - G1 off, G2 on
  - T1 to D2 commutation



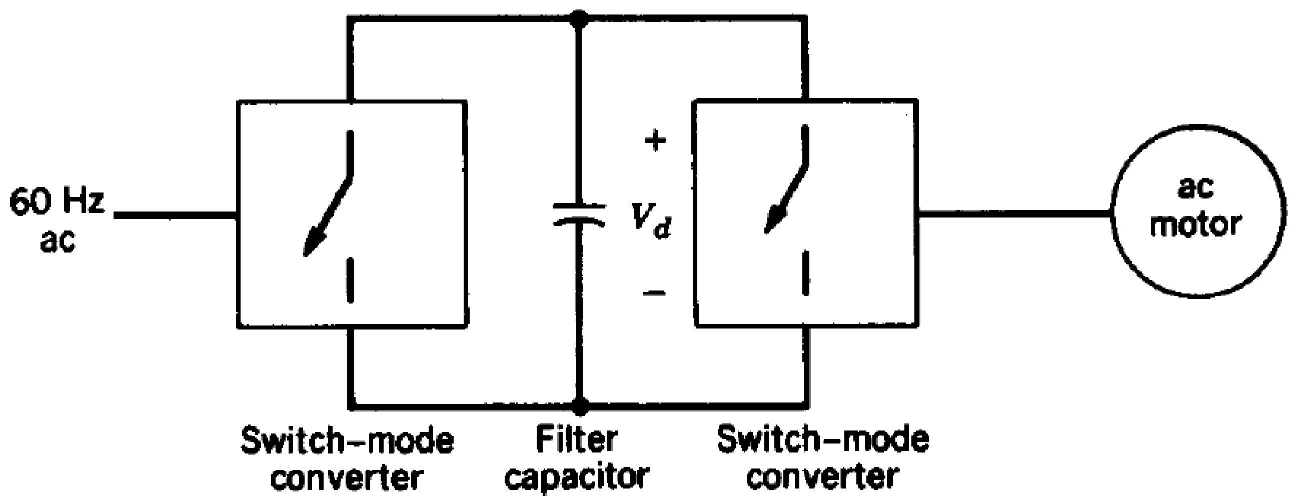
Unidirectional AC-AC converter

- Switch-mode inverter allow power reversal back to DC
- Motor sometimes behaving as a generator
- Use large filter capacitor to temporary store energy from ac motor
- May sometimes add resistor on DC to dissipate energy from motor braking



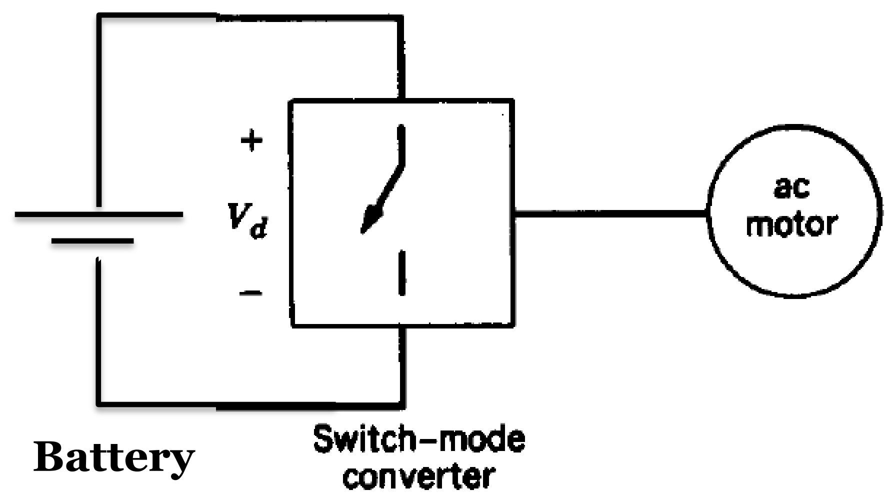
Bidirectional AC-AC converter

- When DC node can not accept all breaking power from ac-motor backfeed into ac-grid is used
- E.g. train braking, HVDC



Bidirectional AC-motor drive

- Battery supplied motor drive
- Regenerative breaking gives battery charging



Lecture 3

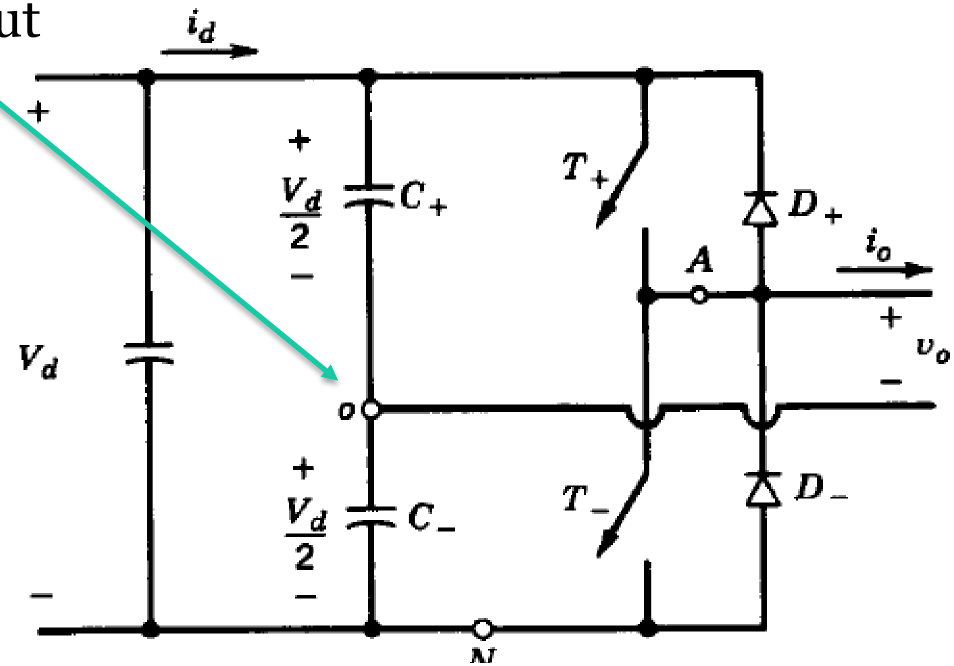
Full-bridge inverter

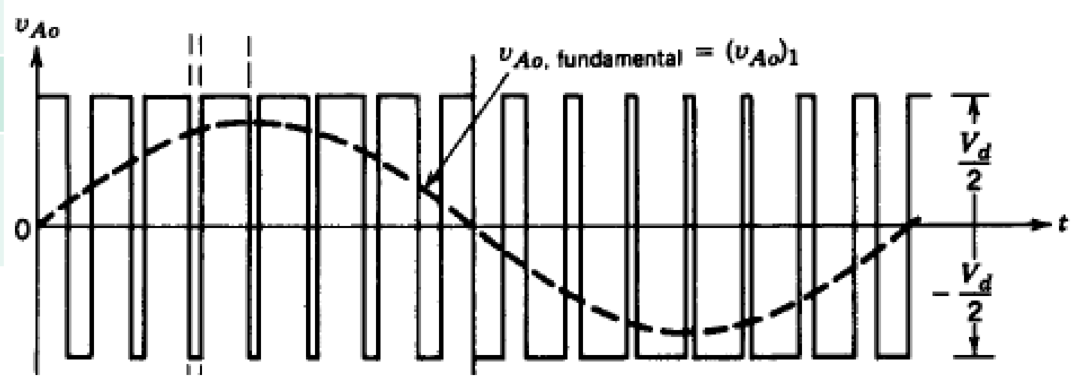
Half-bridge (2-level) converter

$$\hat{V}_{ao1} = m_a \frac{V_d}{2}$$

- DC-side midpoint 'o' reference point for ac-output
- Output voltage switched between $+\frac{V_d}{2}$ and $-\frac{V_d}{2}$
- 4 possible switch states:

T+	T-	
Off	Off	V_o-o def by i_o. $i_o>0$: v_o-o = $-V_d/2$ $i_o<0$: v_o-o = $+V_d/2$
On	Off	v_o-o = $+V_d/2$
Off	**On**	v_o-o = $-V_d/2$
On	**On**	Short circuit. Forbidden state



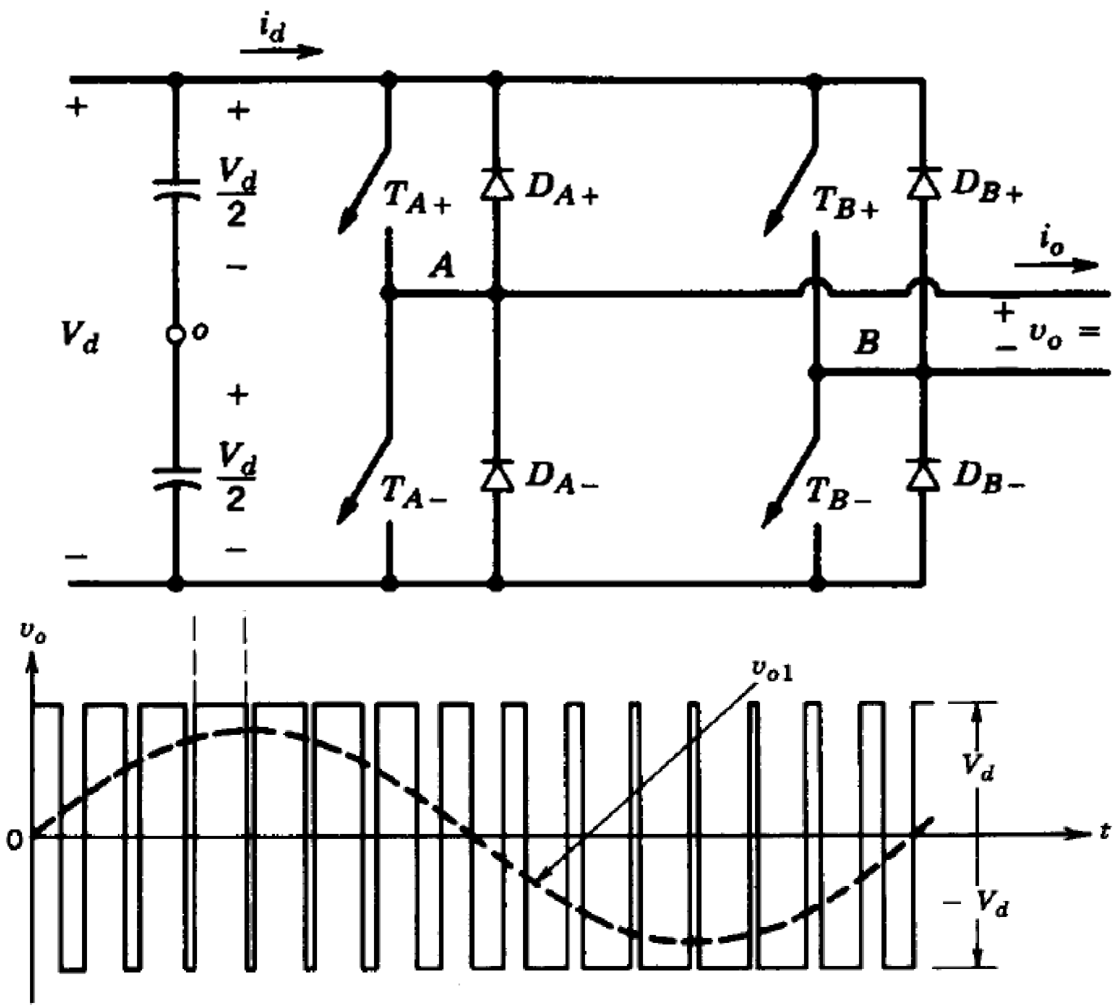


Full-bridge inverter

$$\hat{V}_{o1} = m_a V_d$$

- Maximum output voltage doubled compared to half-bridge inverter
- No need for midpoint voltage

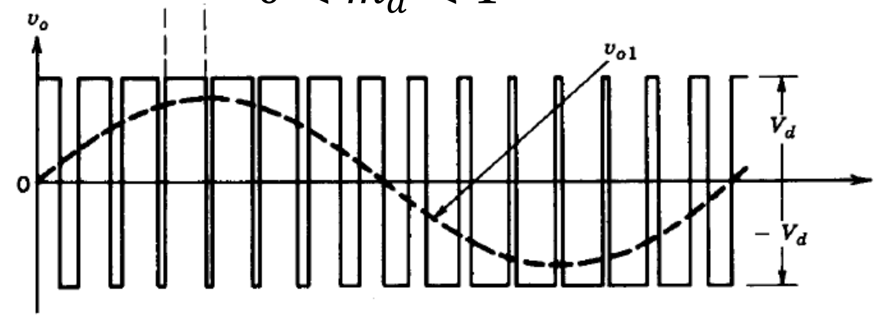
T_{A+}	T_{A-}	T_{B+}	T_{B-}	
Off	Off	Off	Off	Output isolated. Unless $v_o > V_d$ by external source
On	Off	**On**	Off	$v_o = 0$
On	Off	Off	**On**	$v_o = +V_d$
Off	**On**	**On**	Off	$v_o = -V_d$
Off	**On**	Off	**On**	$v_o = 0$
On	**On**	x	x	Short circuit, Forbidden states
x	x	**On**	**On**	



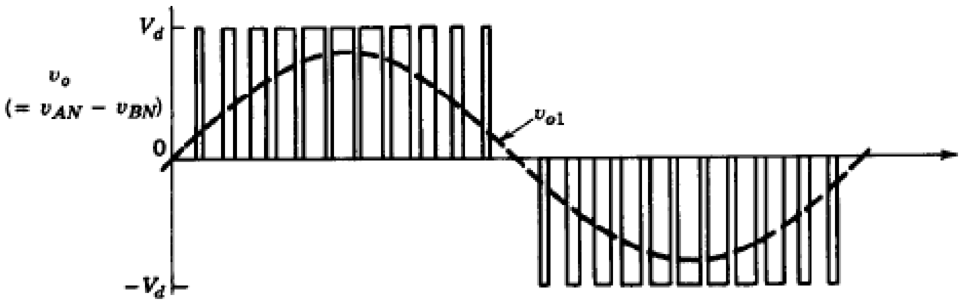
PWM switching strategies

- Bipolar voltage switching
  - Only two states used for (TA+, TA-, TB+, TB-) giving output voltage: $+V_d$ or $-V_d$

$\hat{V}_{o1} = m_a V_d$
$0 < m_a < 1$

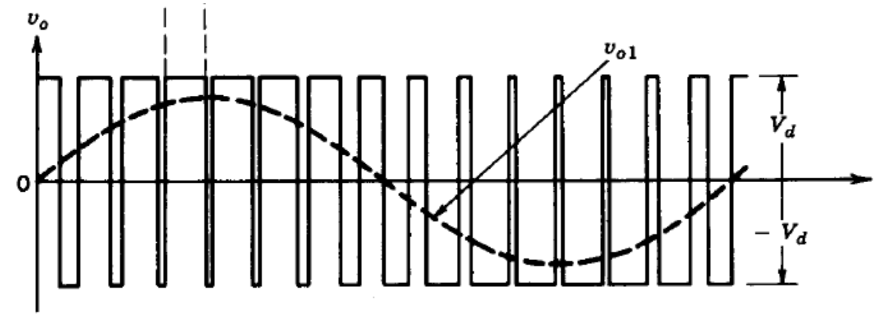


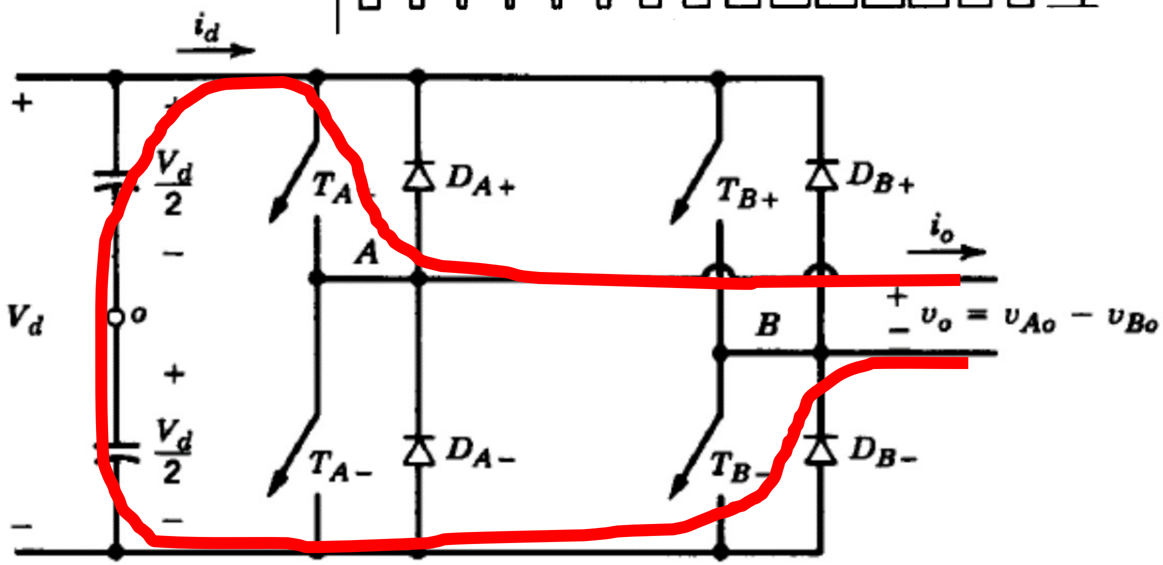
- Unipolar switching
  - All four states used (TA+, TA-, TB+, TB-) giving output voltag $+V_d$, 0 or $-V_d$



PWM bipolar switching

- Bipolar voltage switching
  - Both pairs (TA+, TB-) and (TA-, TB+) controlled simultaneous
- 2 possible switch configurations
  1. **T_{A+} on, T_{B-} on: $v_o = v_A - v_B = +V_d$**
  2. T_{A-} on, T_{B+} on: $v_o = v_A - v_B = -V_d$





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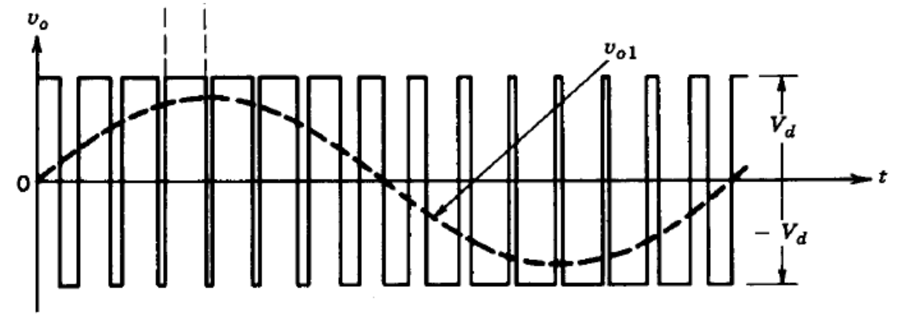
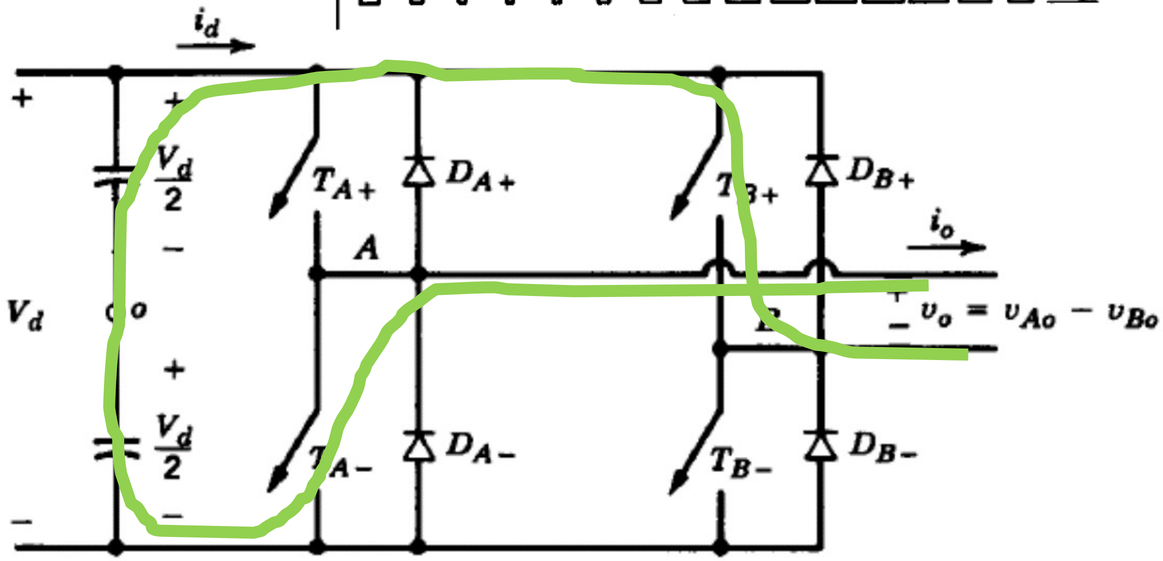




PWM bipolar switching

- Both legs switch at the same time defined by $v_{control}$ and v_{tri}
- When T_{A+} switches on T_{B+} switches off

- Output voltage
  - $\hat{V}_{o1} = m_a V_d$
  - $0 < m_a < 1$

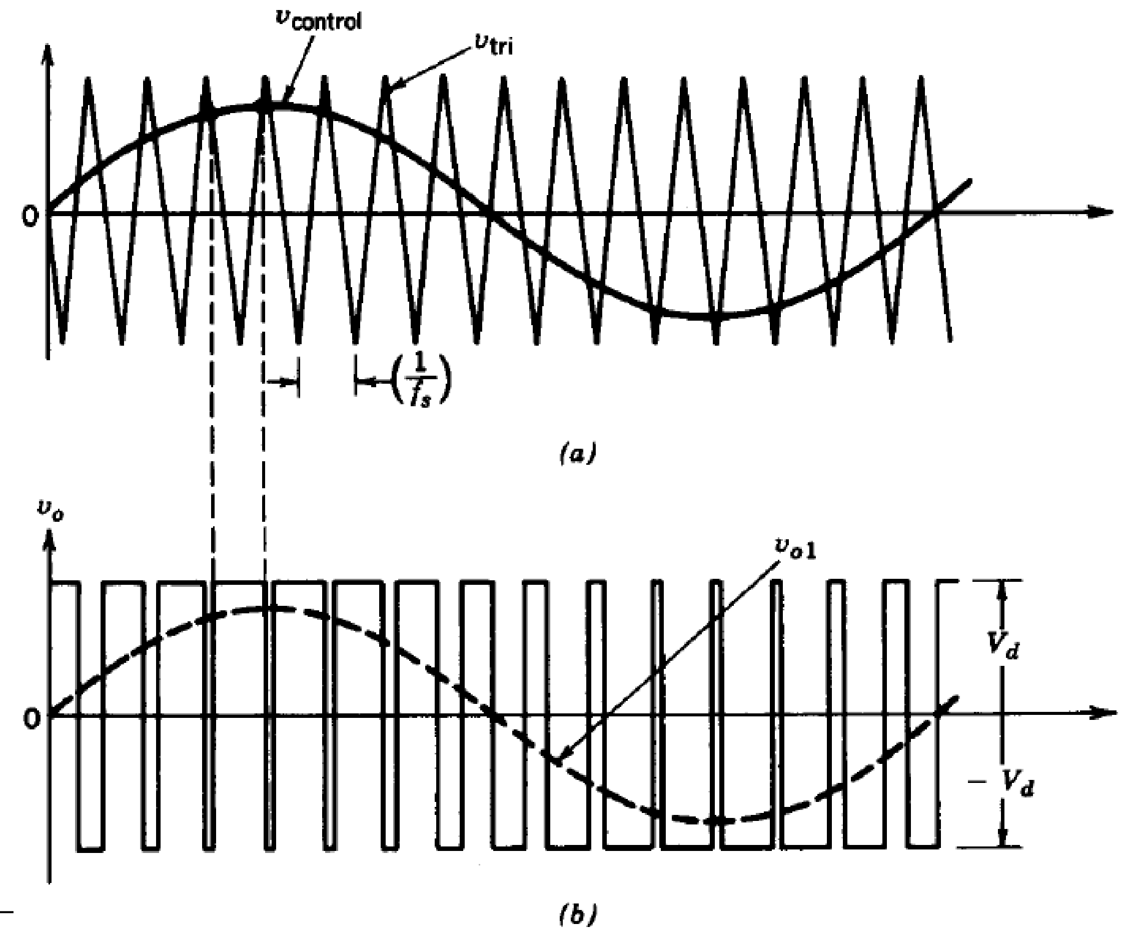
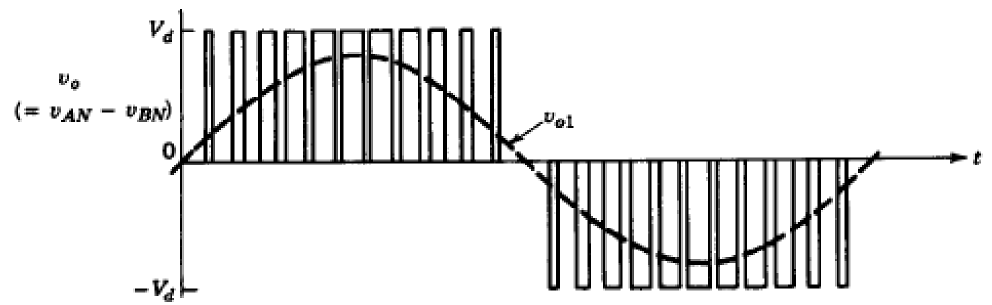


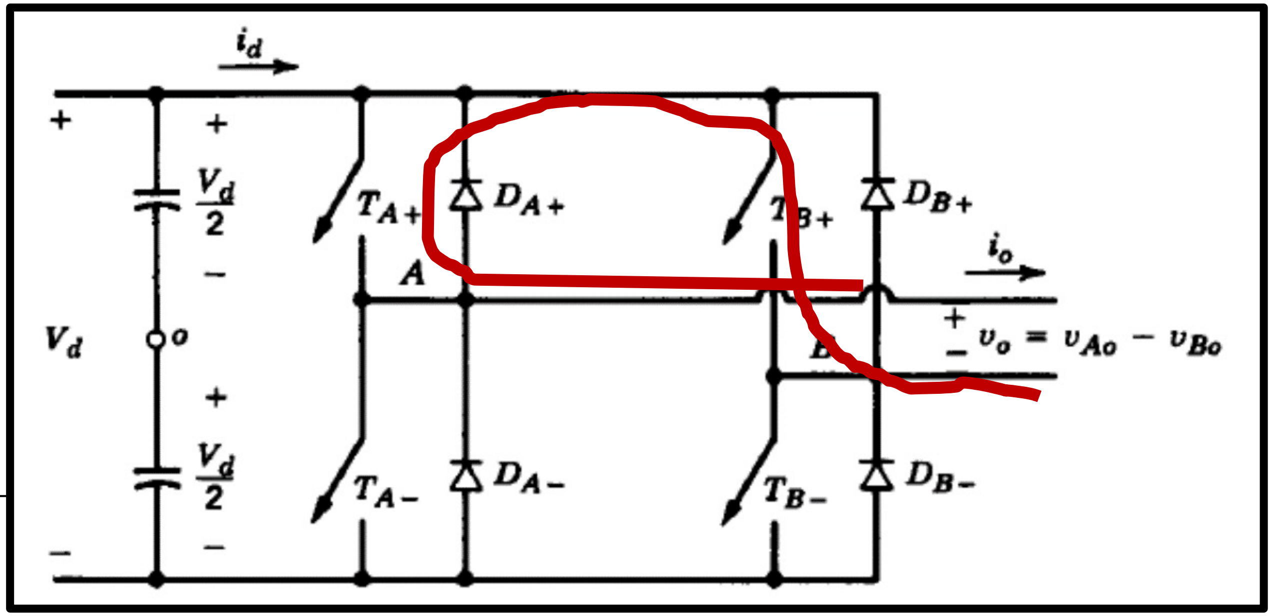
Figure 8-12 PWM with bipolar voltage switching.

Unipolar (3-level) voltage switching

- Switches in each inverter leg (A and B) are controlled independently of the other leg

1. **T_{A+} on, T_{B+} on: $v_o = v_A - v_B = 0$**
2. T_{A+} on, T_{B-} on: $v_o = v_A - v_B = +V_d$
3. T_{A-} on, T_{B-} on: $v_o = v_A - v_B = 0$
4. T_{A-} on, T_{B+} on: $v_o = v_A - v_B = -V_d$





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3. T_{A-} on, T_{B-} on: $v_o = v_A - v_B = 0$
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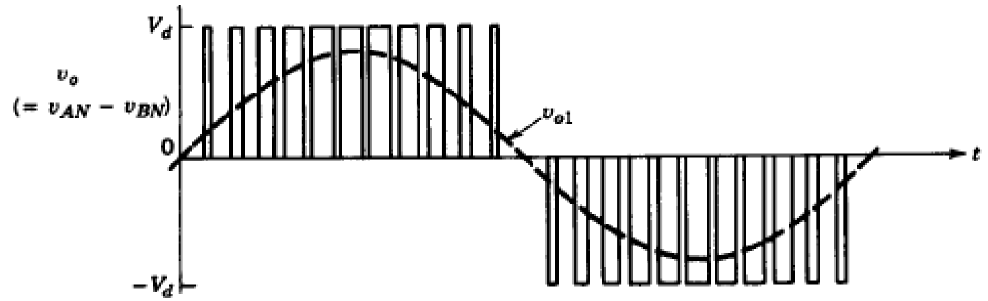

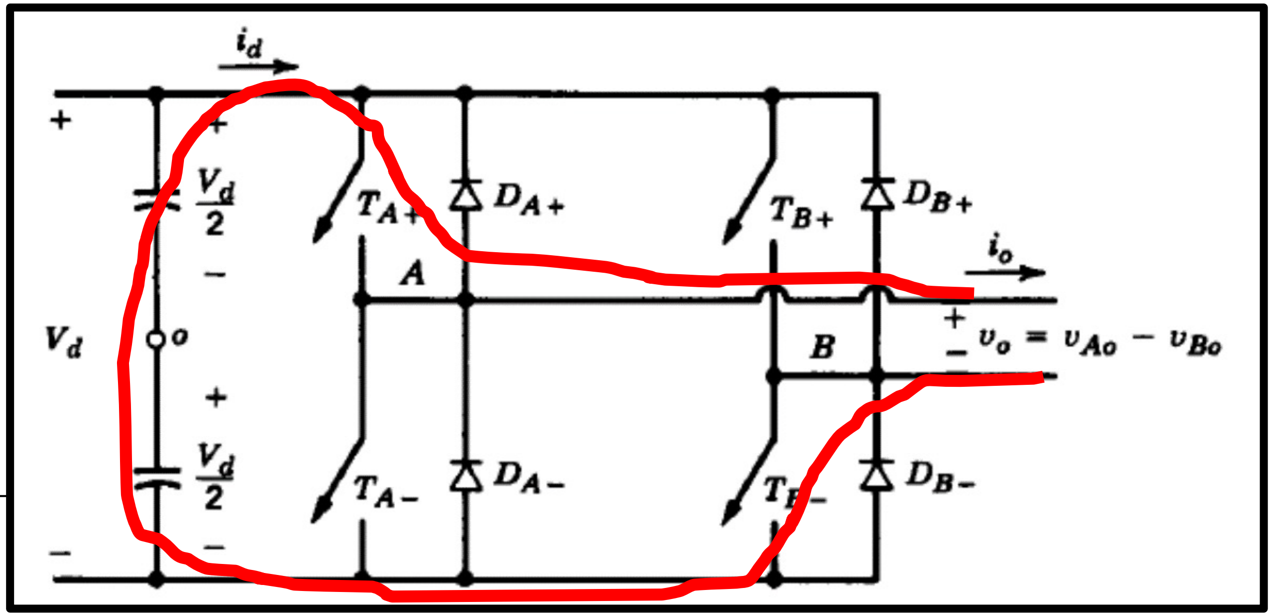

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3. **T_{A-} on, T_{B-} on: $v_o=v_A-v_B = 0$**
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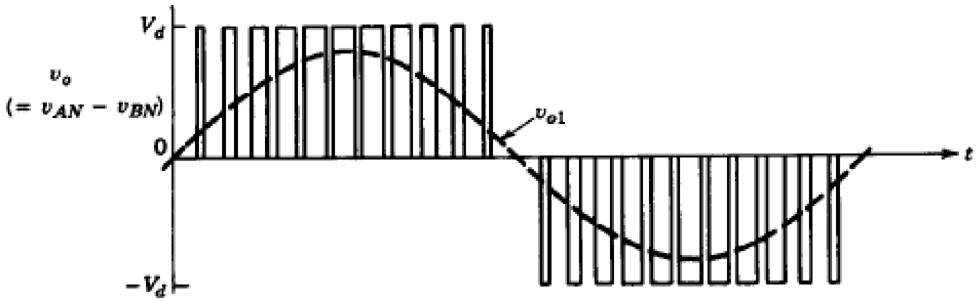

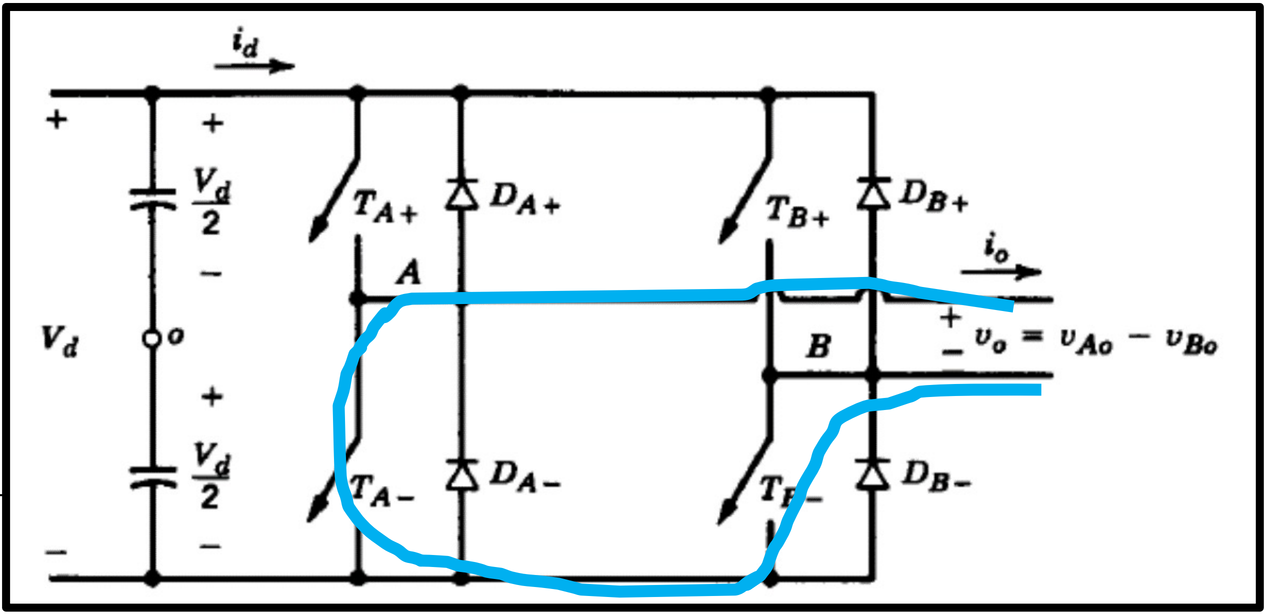

Unipolar (3-level) voltage switching

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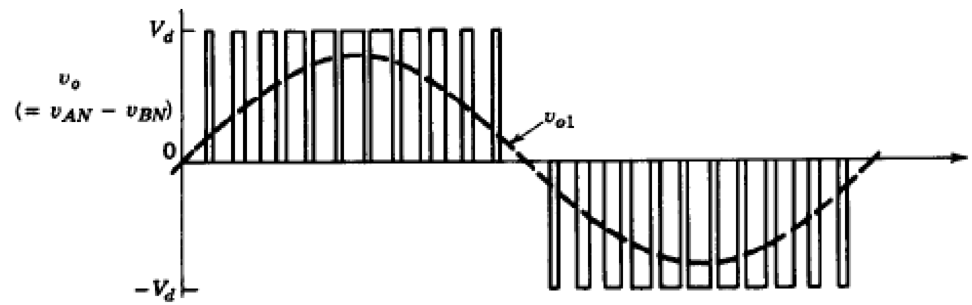
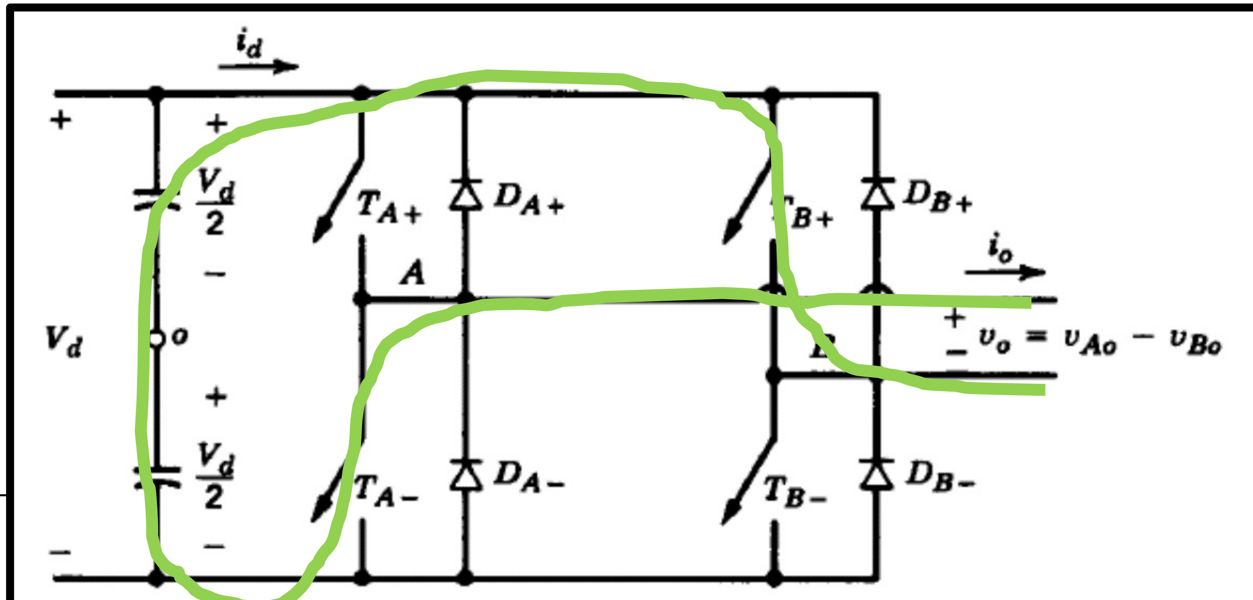
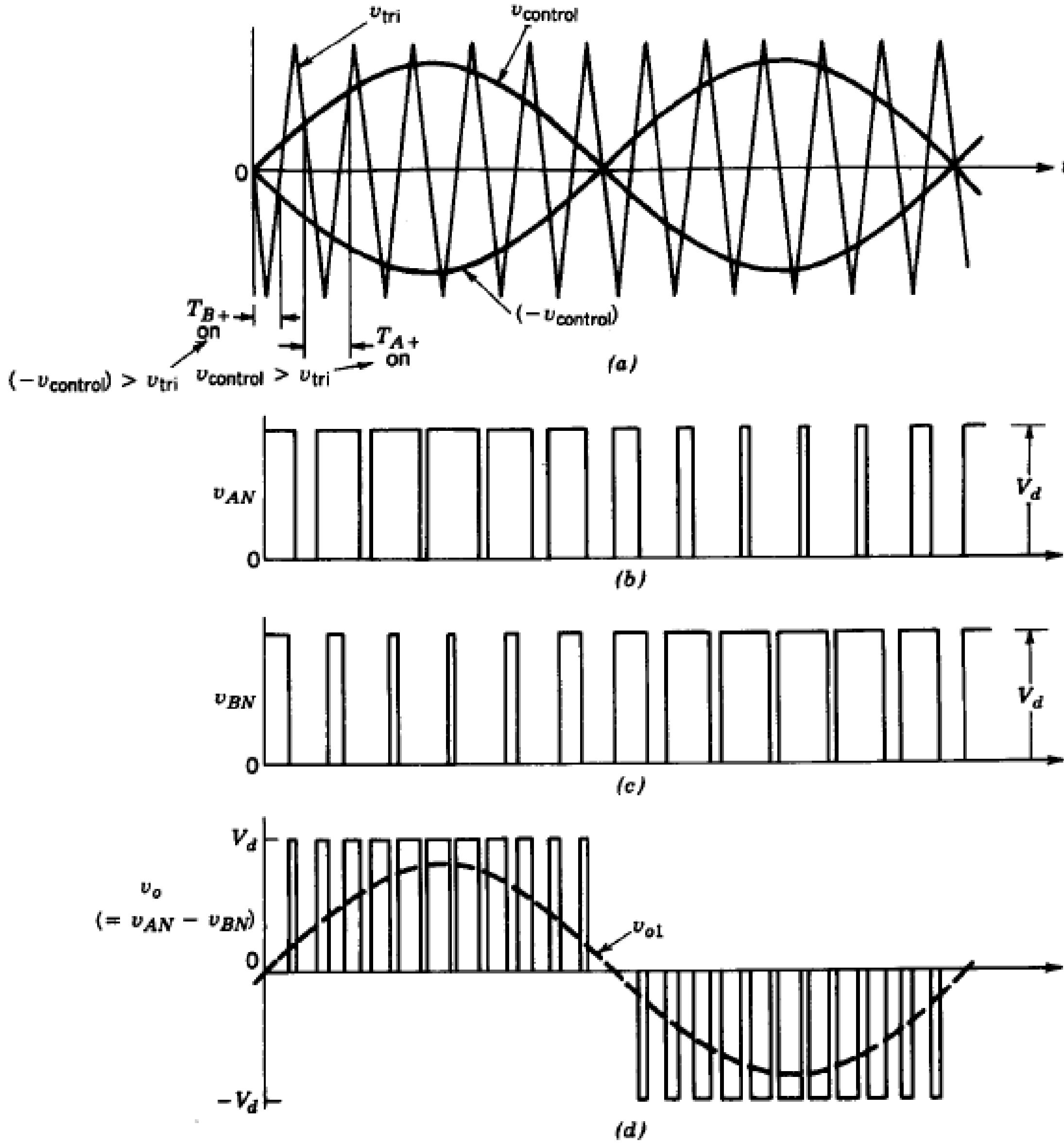




Unipolar PWM-control

- One leg controlled by $v_{control}$
- Other leg controlled by $-v_{control}$
- Four states
- Output voltage
  - $\hat{V}_{o1} = m_a V_d$
  - $0 < m_a < 1$



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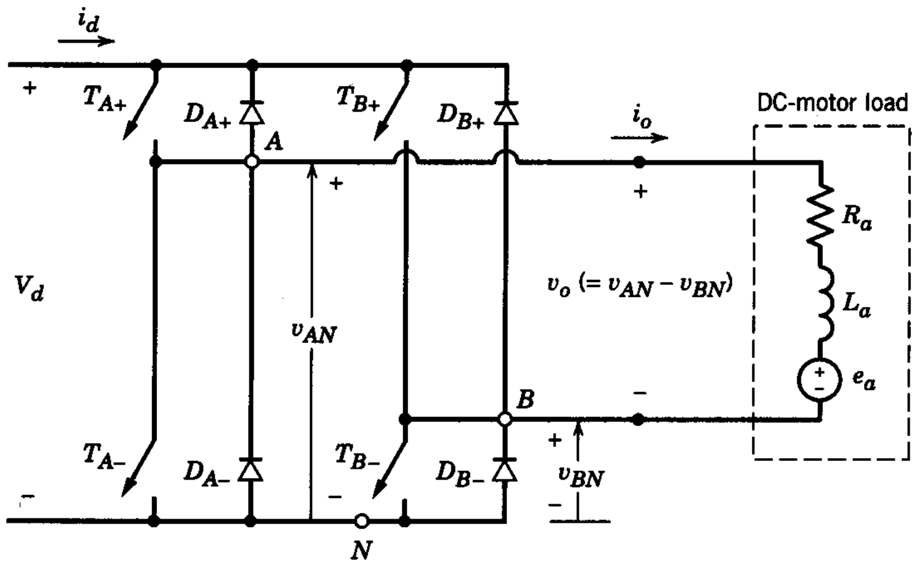
Switch utilization ratio

- The ratio between converter power rating and the combined rating of the switches
- $\frac{V_{o1,max} I_{01,max}}{q V_T I_T}$
- $V_{o1,max}$ max fundamental output rms voltage
- $I_{01,max}$ max fundamental output rms current
- q: number of switches
- V_T: Peak voltage rating a switching device
- I_T: Peak current rating of a switching device

Lecture 3

Full-bridge DC/DC converter

Full-bridge DC/DC converter



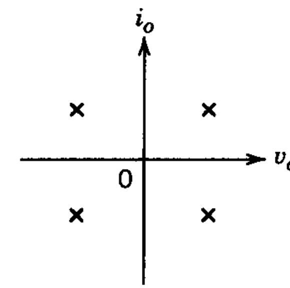


Figure 7-27 Full-bridge dc–dc converter.

- Four quadrant operation is possible.
  - Positive or negative output voltage
  - Bidirectional current
- Common for dc-motor drives
  - Bidirectional rotation
  - Both motor and generator operation

Converter Waveforms

- Bi-polar voltage switching

$$D_1 = \frac{t_{on}}{T_s} = \frac{1}{2}\left(1 + \frac{v_{control}}{\hat{V}_{tri}}\right)$$

$$D_2 = 1 - D_1$$

$$V_o = V_{AN} - V_{BN} = D_1 V_d - D_2 V_d$$

$$= (2D_1 - 1)V_d$$

$$V_o = \frac{V_d}{\hat{V}_{tri}} v_{control}$$

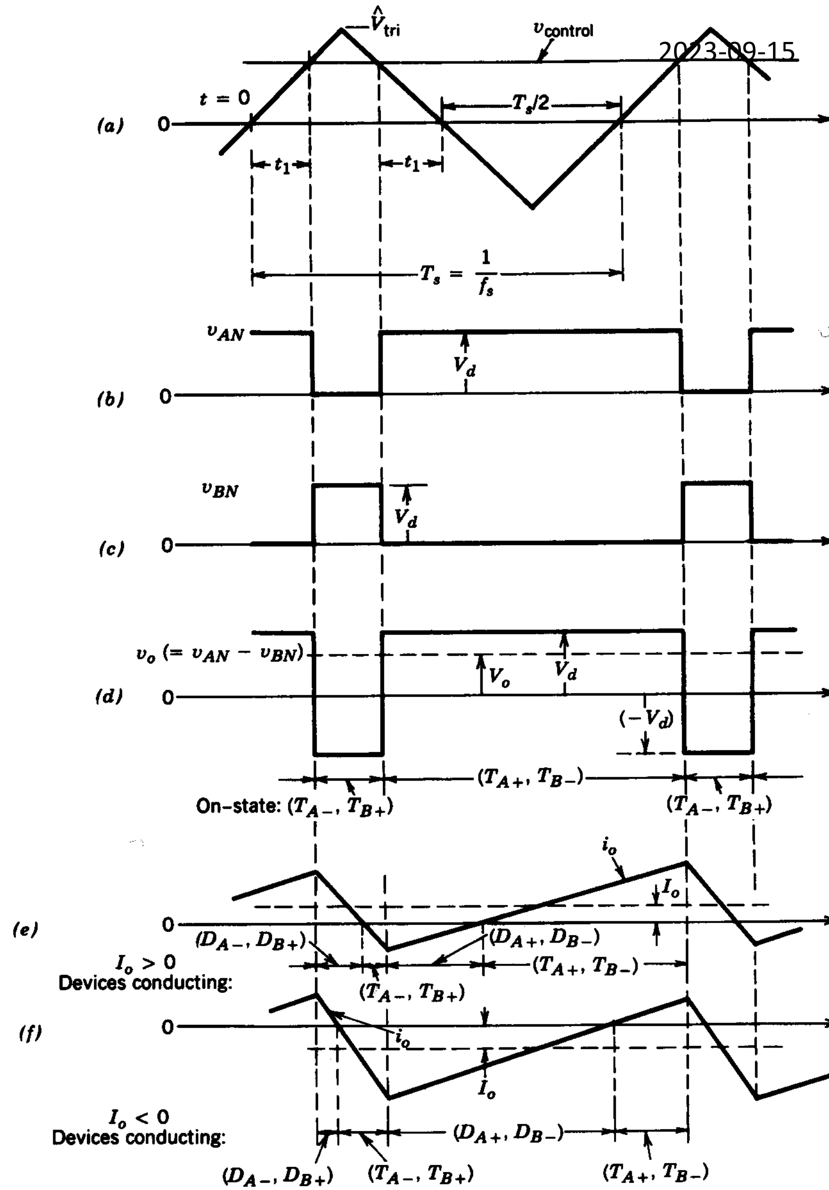


Figure 7-28 PWM with bipolar voltage switching.

Converter Waveforms

- Uni-polar voltage switching

$$D_1 = \frac{1}{2}\left(\frac{v_{\text{control}}}{\hat{V}_{\text{tri}}} + 1\right) \qquad T_{A+}$$

$$D_2 = 1 - D_1 \qquad T_{B+}$$

$$V_o = (2D_1 - 1)V_d = \frac{V_d}{\hat{V}_{\text{tri}}}\, v_{\text{control}}$$

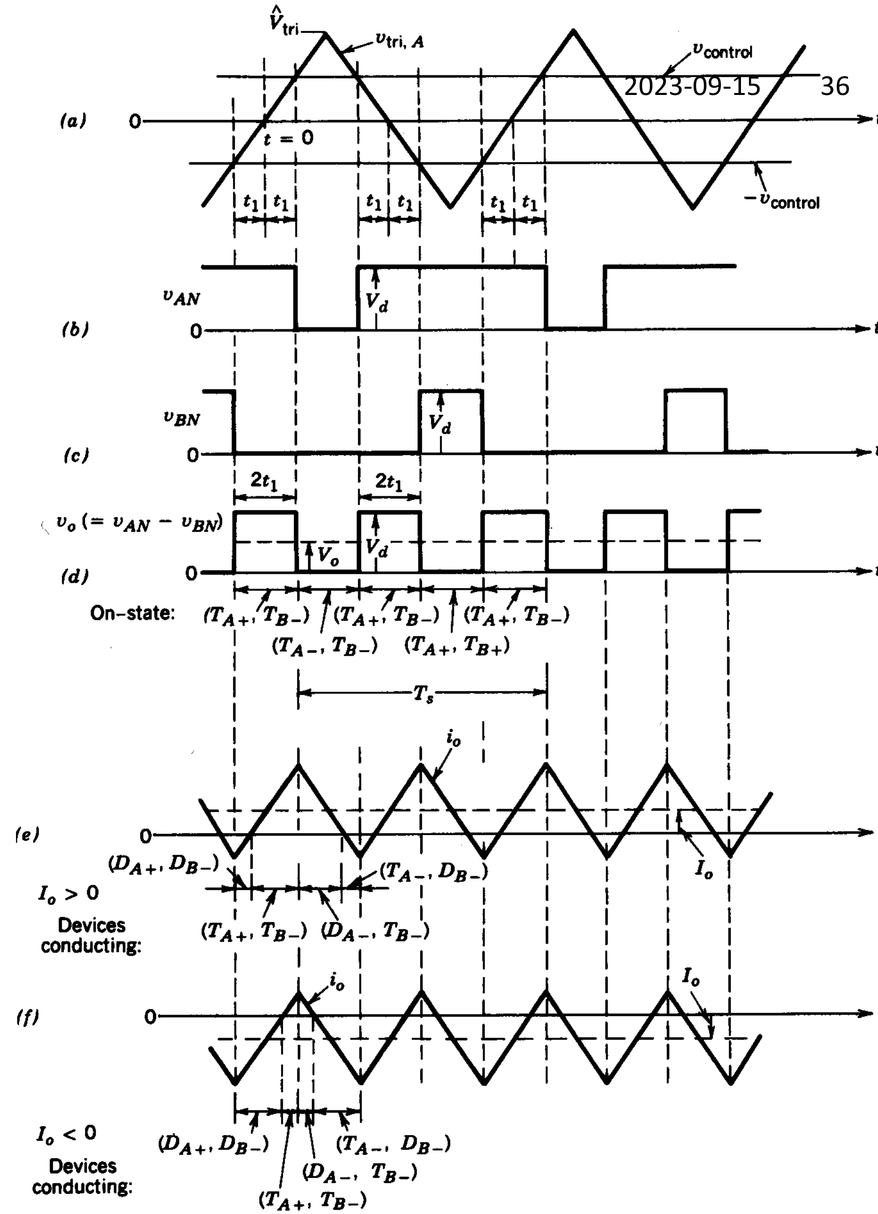


Figure 7-29 PWM with unipolar voltage switching.

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