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ENM061 - Power Electronic Converters 7.5 ECTS, 2017

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Lecture outline

The single-phase inverter

- Power flow direction and definition of inverter/rectifier stage
- Revisiting the H-bridge converter
- The single-phase inverter in square-wave operating mode
- The single-phase inverter in bipolar-PWM operating mode
- The single-phase inverter in unipolar-PWM operating mode
- Output voltage and current ripple with a back-EMF load
- Summary

Learning outcomes

- Fourier components and total harmonic distortion (THD) for basic waveforms.
- Operating principles of the most common active components (e.g. diode, thyristor, IGBT, and MOSFET) and passive components (e.g. capacitors, transformers and inductors).
- Operation of a pulse width modulation (PWM), the purpose of controlling the desired quantity and the need for a controller circuit within the power electronic converter.
- Analysis of ideal DC/DC converters (e.g. buck, boost, buck-boost, flyback, the forward, the push-pull, half-bridge and full-bridge converters) in CCM and DCM operation.
- Operating principles of single-phase and three-phase DC/AC inverters with different modulation strategies (e.g. PWM and square wave operation).
- Operation of multilevel converters (e.g. NPC, flying capacitor and MMC topologies) using current and voltage waveform analysis. Pros and Cons of the converter in terms of harmonics and losses.
- Operation of single- and three-phase diode rectifiers operating with voltage-stiff and current-stiff DC-side. Investigating the impact of line impedance within the converter circuit for current commutation.
- Operation of single- and three-phase thyristor rectifiers operating with a current-stiff DC-side and the impact of line impedance for current commutation. Investigating the use of 6/12-pulse configurations.
- Identify simple power electronic converter schematics. Recognizing the different parts in a physical circuit on which basic wave-shape and efficiency measurements is performed.
- Loss calculation in passive and active components. Evaluating the temperature rise in the active components and choosing an appropriate heat-sink. Gaining a basic understanding of component life time.
- Utilizing the software Cadence PSpice to simulate basic power electronic circuits and the practical labs to have a firsthand experience of how real DC/DC converters operate.

Power Flow direction Rectifier vs Inverter stage

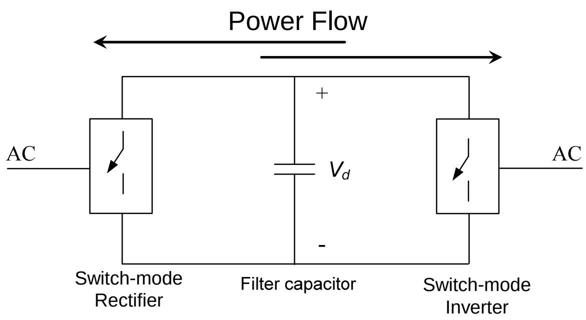

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Figure 8-2, page 201

- AC-AC converter as a whole
- The inverter transforms DC to AC with a controllable voltage and/or frequency
- A rectifier transforms AC of any frequency to DC
- Examples: motor drives, uninterruptible power supplies (UPS), grid-connected converters (active filters, FACTS, HVDC)

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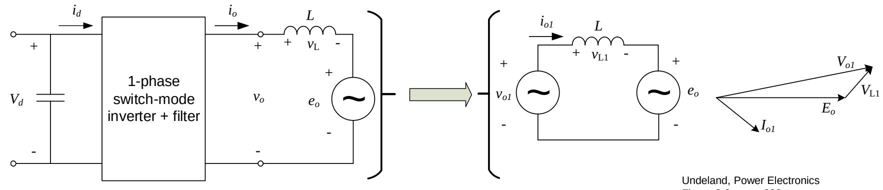
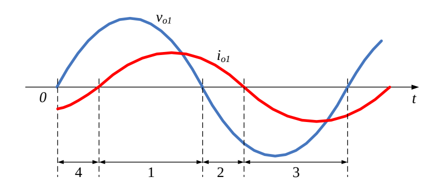
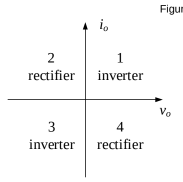
Power Flow direction the inverter stage

- Consider a motor drive system where the load can typically be represented with a large inductance and a back-EMF as $e_0 = \sqrt{2}E_0 \sin(\omega t)$
- Due to the phase difference between the current and voltage, the inverter has to be able to operate in all four quadrants.







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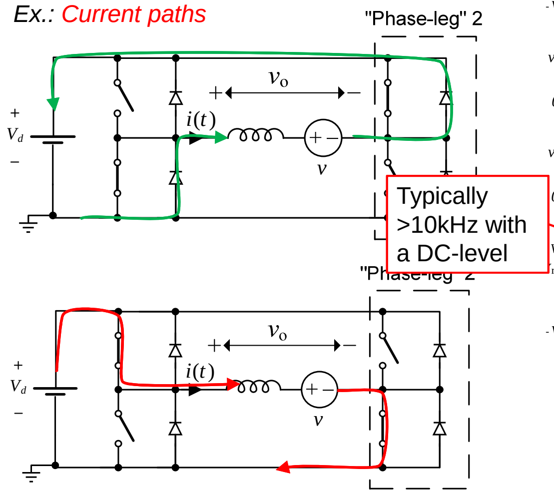
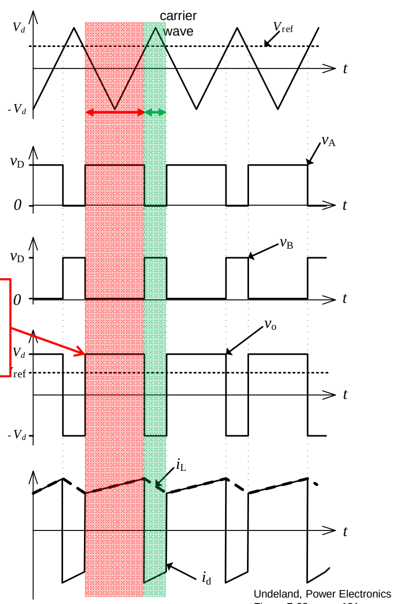
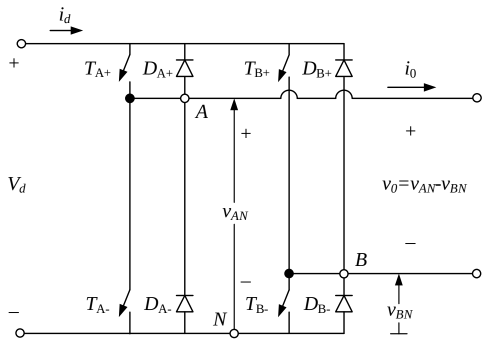
Revisiting the H-Bridge DC/DC Converter

Ex.: Current paths





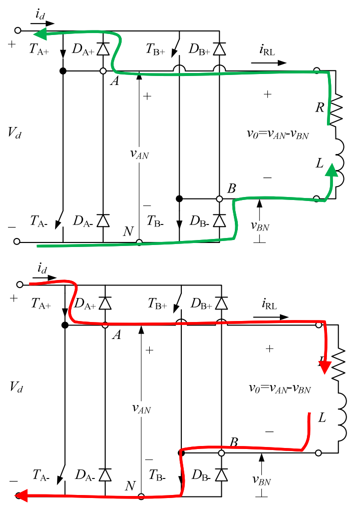
Single-Phase Inverter
Different Operating Modes

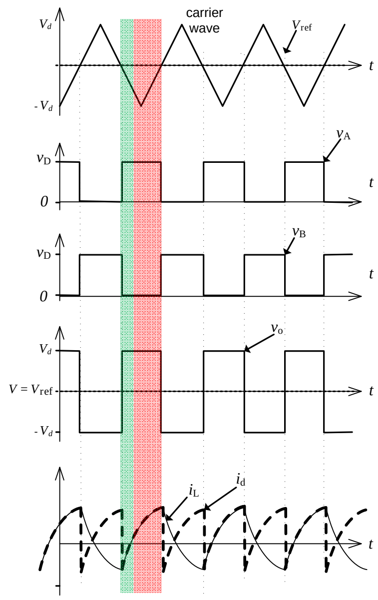


- Square-wave operation
- Bipolar-PWM switching
- Unipolar-PWM switching

Single-Phase Inverter
Square-Wave Mode

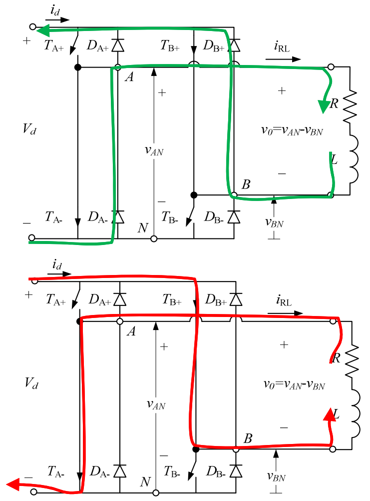
Ex.: *Current paths*

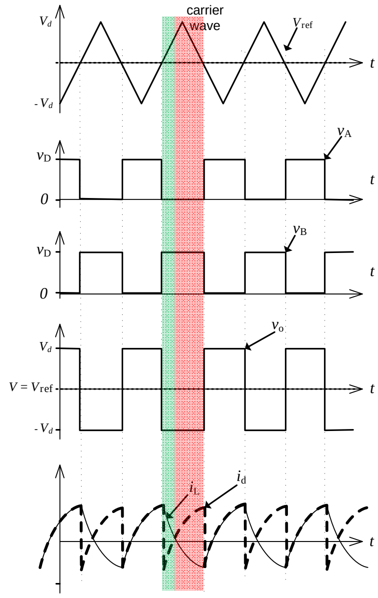




Single-Phase Inverter Square Wave Mode

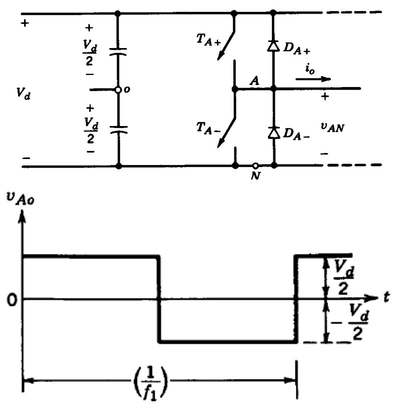
Ex.: Current paths



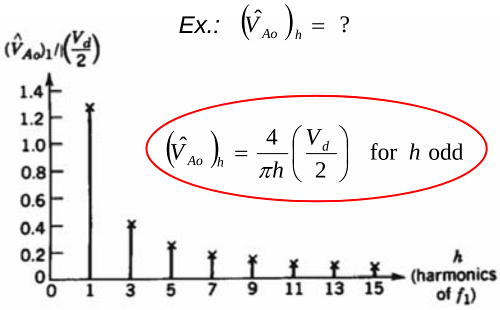


Single-Phase Inverter Square Wave Mode

- The output voltage of an inverter operating in square-wave mode results in a high number of odd harmonics



Ex.: $(\hat{V}_{Ao})_h = ?$



$$(\hat{V}_{Ao})_h = \frac{4}{\pi h}\left(\frac{V_d}{2}\right) \quad \text{for } h \text{ odd}$$

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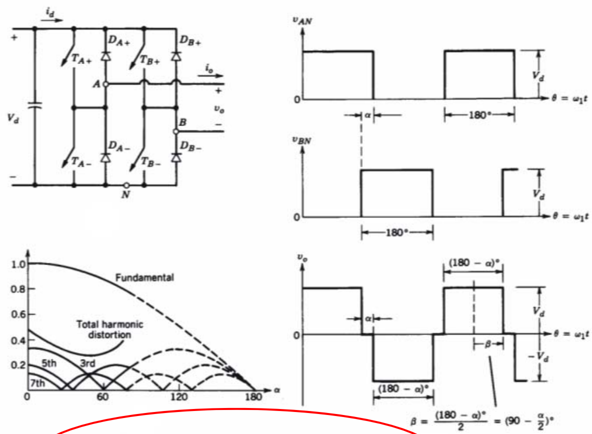
Single-Phase Full-bridge Inverter Square-Wave + Unipolar Switching



$$\left(\hat{V}_{Ao}\right)_h = \frac{4}{\pi h} V_d \sin(h\beta) \text{ for } h \text{ odd}$$

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Figure 8-17, page 219

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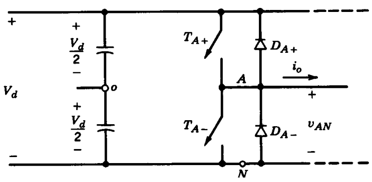
Single-Phase Inverter Bipolar Switching and Voltage Control

- Compare the reference voltage with a triangular voltage with much higher frequency – bipolar swtiching



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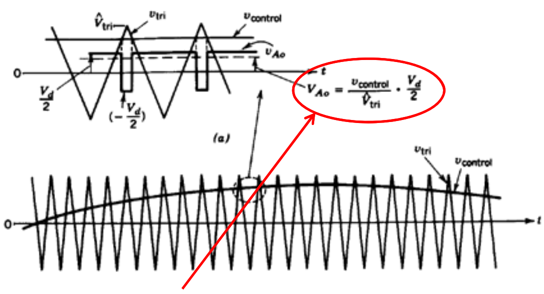

$$V_{Ao} = \frac{v_{control}}{\hat{V}_{tri}} \cdot \frac{V_d}{2}$$

Valid in the linear range (m_a<=1) for the half-bridge phase leg!

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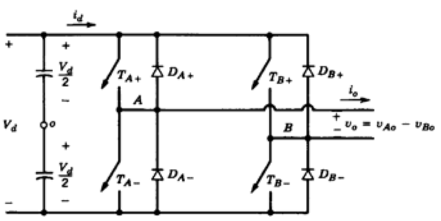
Single-Phase Inverter
Bipolar Switching and Voltage Control

- Compare the reference voltage with a triangular voltage with much higher frequency – bipolar swtiching as for a H-bridge DC/DC-converter



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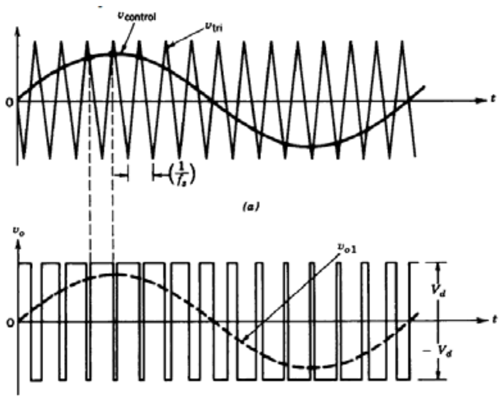

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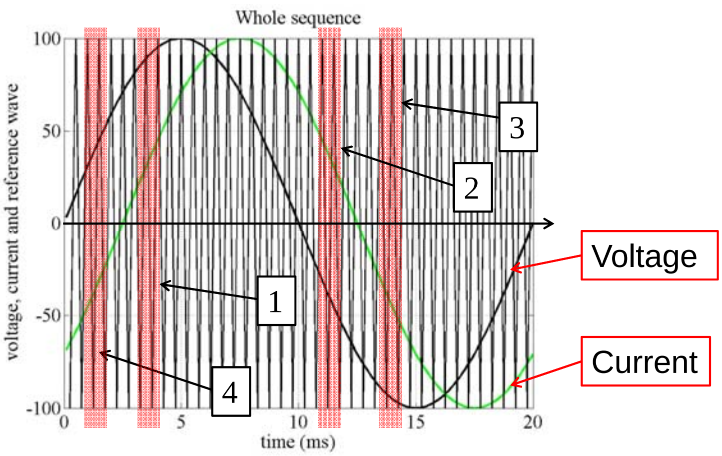
Single-Phase Inverter
Bipolar Switching and Current Paths



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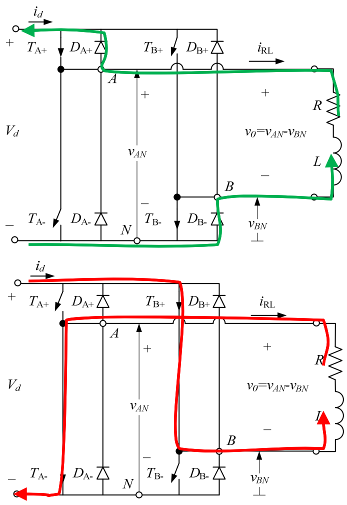
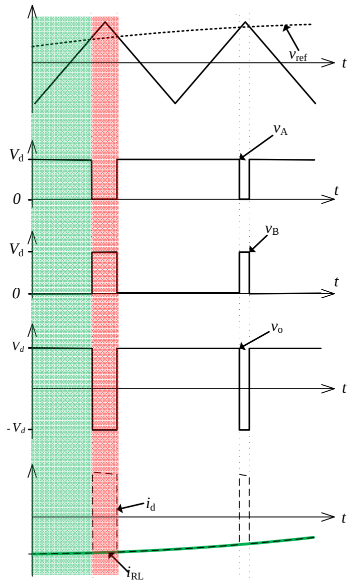
Bipolar Switching Current Path 1

Ex.: Current paths





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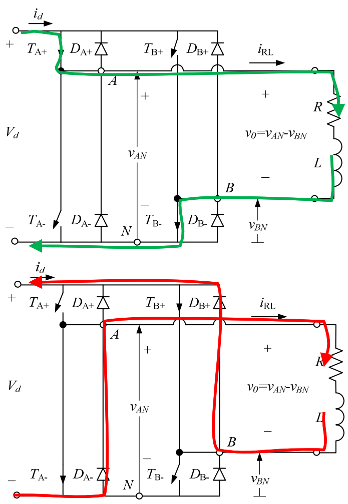
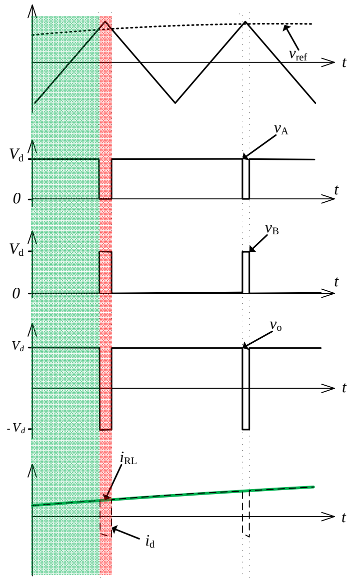
Bipolar Switching Current Path 2

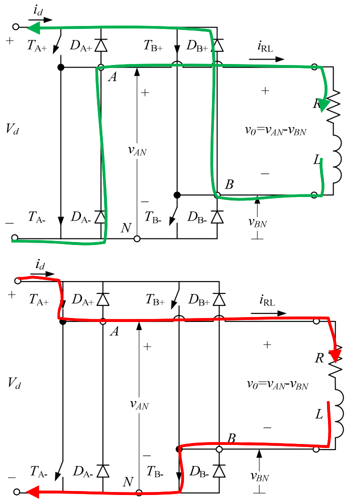
Ex.: Current paths

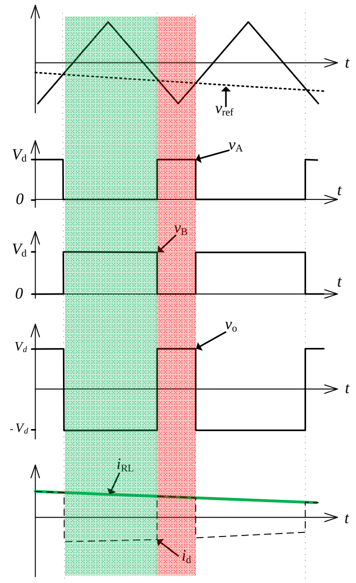




Bipolar Switching Current Path 3

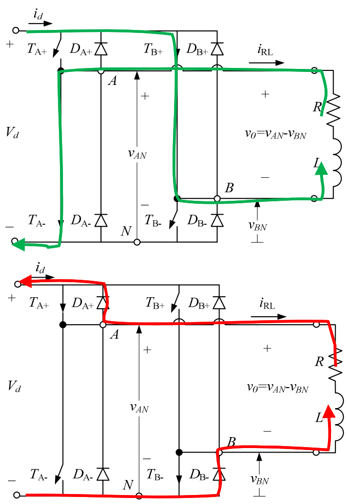
Ex.: *Current paths*

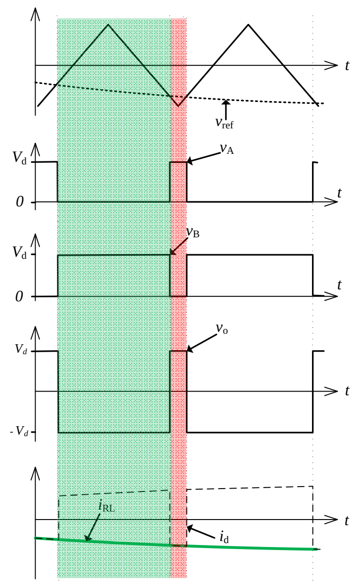




Bipolar Switching Current Path 4

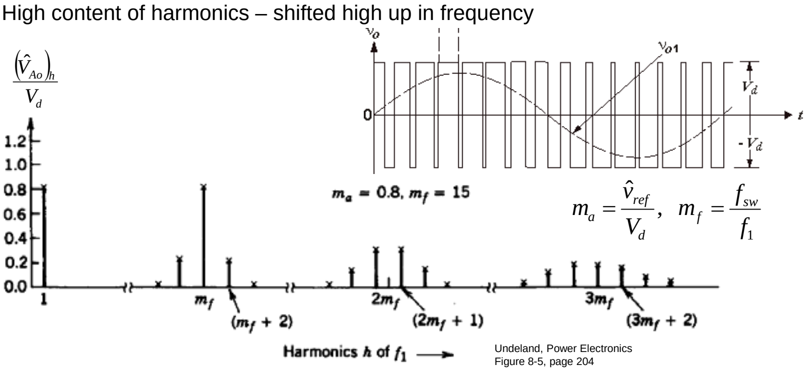
Ex.: *Current paths*





Single-Phase Inverter
Harmonics in Bipolar Switching

- High content of harmonics – shifted high up in frequency



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- Synchronous PWM: when the control voltage and the carrier are synched (when $m_f \leq 21$).
- Asynchronous PWM: when m_f is not an integer. Creates unwanted subharmonics of the fundamental frequency component (OK when $m_f \geq 21$)

Single-Phase Inverter
Harmonics in Bipolar Switching

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.

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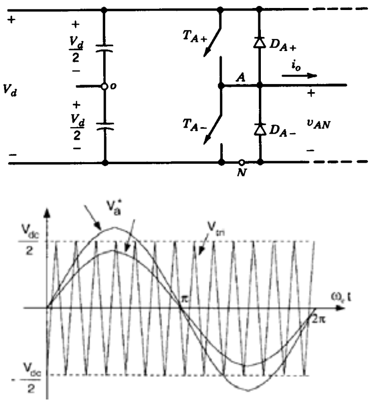
Table 8-1, page 207

- Harmonics appear as side bands at multiples of the switching frequency

Single-Phase Inverter – Modulation Index with Bipolar Switching

- An increased modulation index gives over modulation – the linear relationship between m_a and V_d is no longer valid



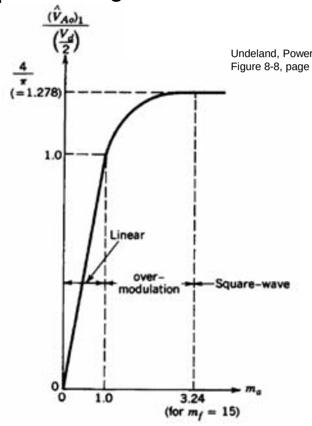


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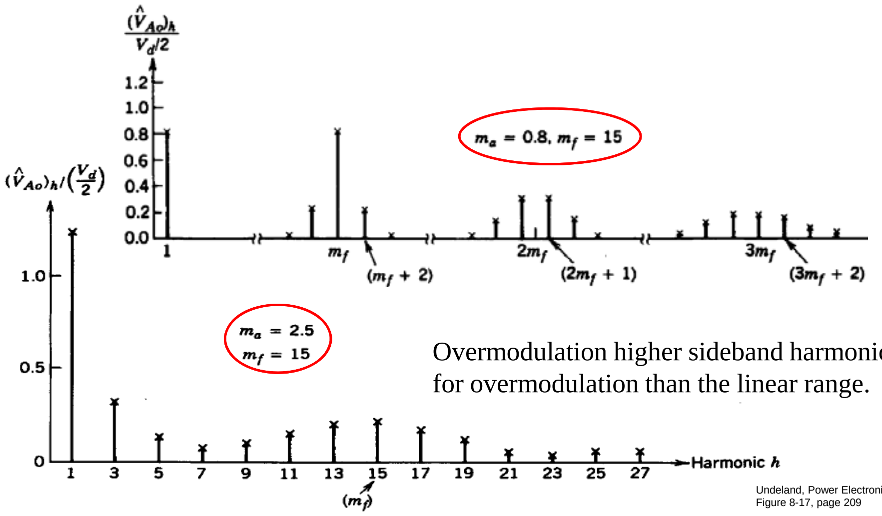
Figure 8-8, page 209

Single-Phase Inverter – Harmonics and Over-Modulation



Overmodulation higher sideband harmonics for overmodulation than the linear range.

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Figure 8-17, page 209

Single-Phase Inverter – DC-Side Current Ripple in Bipolar Switching

- The inverter input current (i_d) consists of i_d* and the high frequency components due to the inverter switchings

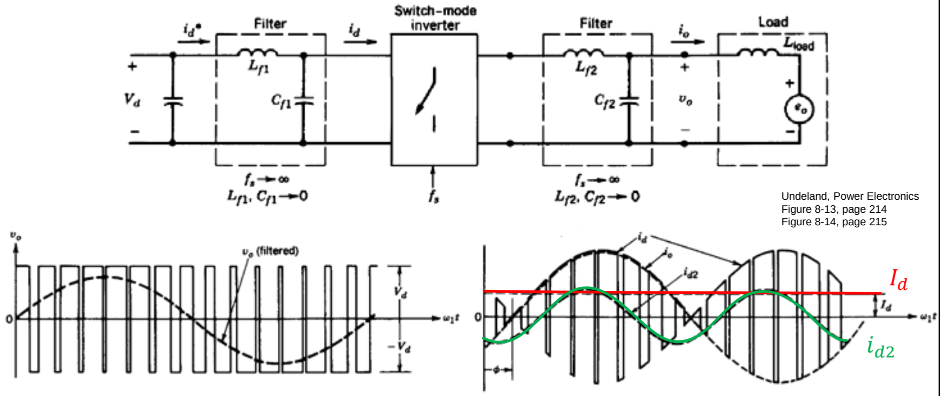

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Figure 8-14, page 215

Single-Phase Inverter Unipolar Switching

- Legs A and B are controlled by comparing v_{tri} with $v_{control}$ and $-v_{control}$ respectively.

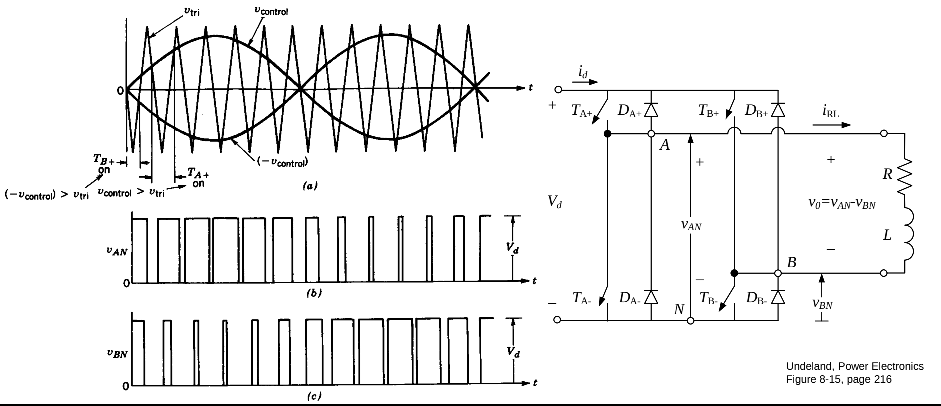

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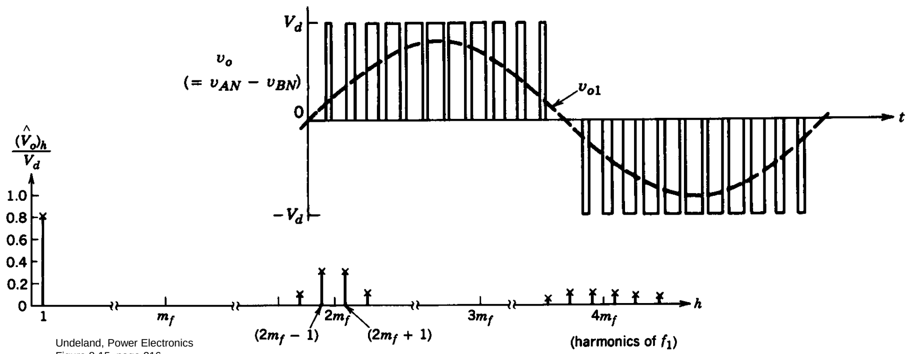
Figure 8-15, page 216

Single-Phase Inverter Unipolar Switching

- The load experiences a doubled switching frequency with lower harmonic content



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Single-Phase Inverter DC-Side Current in Unipolar Switching

- PWM with unipolar switching results in lower ripple on the DC-side current compared with bipolar switching

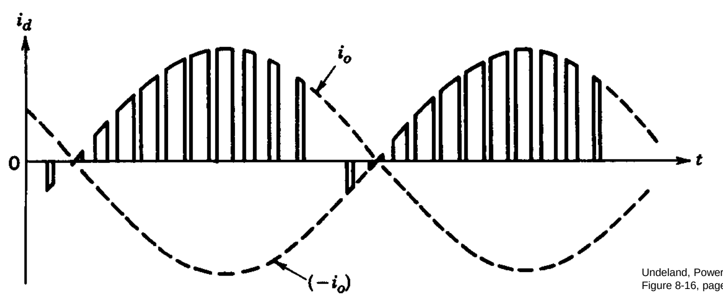

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Figure 8-16, page 218

Single-Phase Inverter Output Ripple Current

- The inverter supplies an induction motor represented by a back-emf
- Only the fundamental frequency sinusoidal component transfer real power
- Fundamental and higher frequency ripple components can be separated – the current ripple is formed by the voltage over the inductor

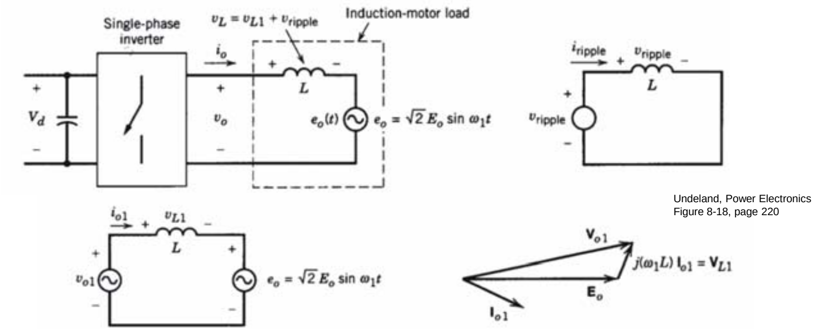

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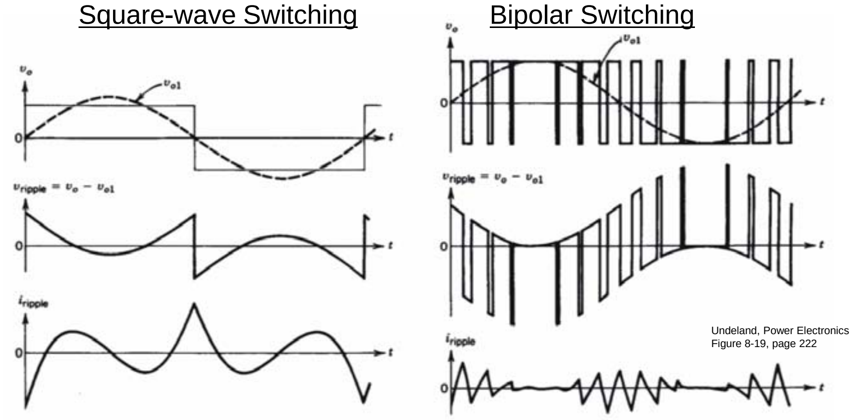
Figure 8-18, page 220

Single Phase Inverter Output Ripple Current

Square-wave Switching | Bipolar Switching



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- PWM switching gives lower current ripple for the same load

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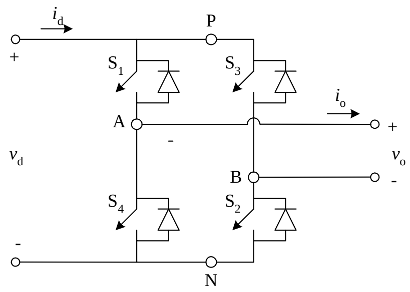
Tutorial 7



- PWM: $295 \le V_{dc} \le 325$, $m_a \le 1.0$ for low distortion, max($V_{o(1)}$ on nameplate)?
- Square: $V_{dc}=300$; purely inductive load with back-emf e_o; $V_{o(1)} = e_o$;

  Calculate $V_{o(1)}$, sketch the current ripple and find its peak value
- Square: purely inductive load, plot output voltage and current waveforms

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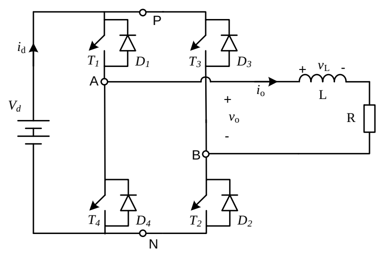
PSpice 4



Square-wave vs PWM (bi- and uni-polar switching) for the same v_o

- Load voltage and current waveforms
- Calculate and compare the load voltage and current harmonic components
- Impact of unipolar switching over bipolar switching

Summary

- Power flow direction and definition of an inverter/rectifier stage
- Pros and cons of square wave vs. PWM operating mode
- Pros and cons of bipolar vs. unipolar PWM operating mode
- Estimation of harmonics in the output current and voltage of inverters
- Learning outcome:
  - Operating principles of a single-phase DC/AC inverter with different modulation strategies (e.g. PWM and square wave operation).