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ENM061 - Power Electronic Converters 7.5 ECTS, 2017

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Lecture outline

The three-phase inverter

- Three-phase inverters – basic operating principle
- Three-phase inverters – Square-wave operating mode and current paths
- Three-phase inverters – PWM operating mode and current paths
- Three-phase inverters – output current ripple
- Impact of blanking time
- Other switching strategies
- Summary

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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.

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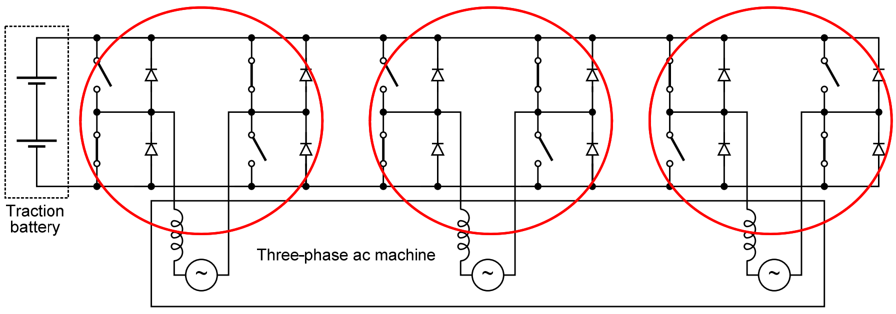
Three-Phase Inverter

- A three phase inverter can be designed with three single phase inverters – complex design!



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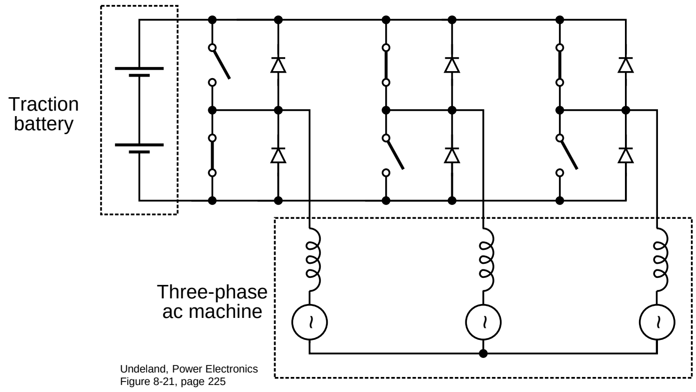
Three-Phase Inverter

- Sum of currents and voltages should be zero in a three-phase system



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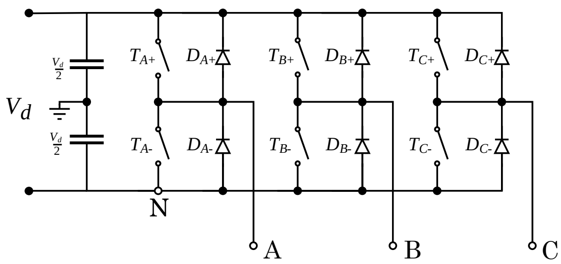
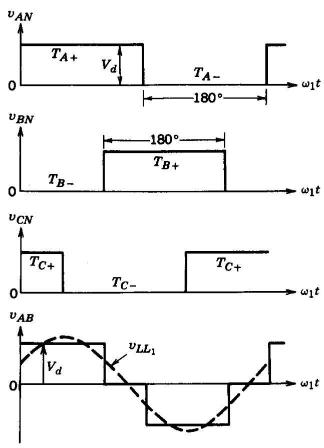
Three-Phase Inverter Square Wave Mode

$$v_{AB} = v_{AN} - v_{BN}$$





Ex: Show which switch is on at various time intervals

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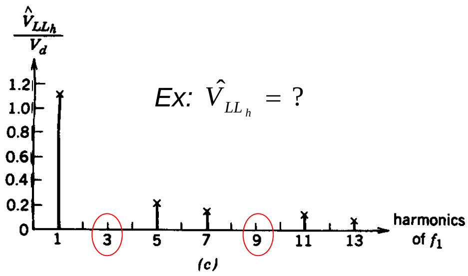
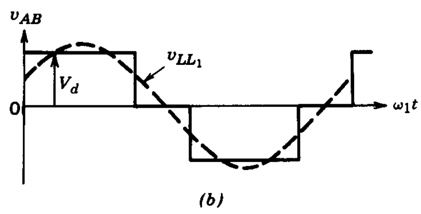
Figure 8-24, page 230

Three-Phase Inverter Square Wave Harmonics

- The line-to-line voltage does not depend on the load
- Contains harmonics (6n±1, n=1,2,…)



Ex: $\hat{V}_{LL_h} = ?$



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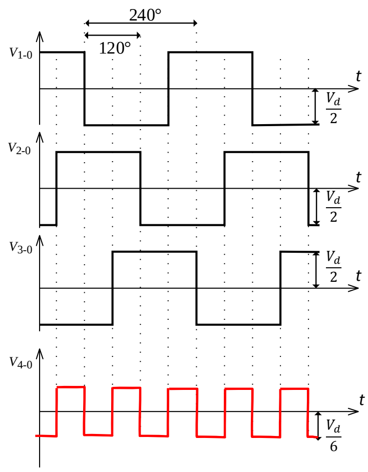
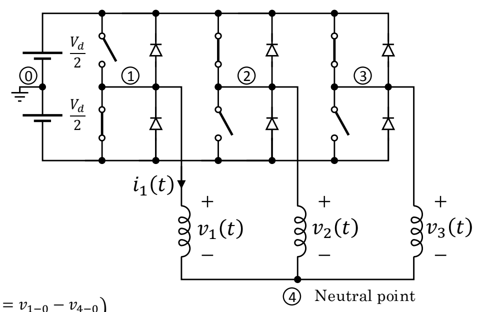
$$\hat{V}_{LL_h} = \frac{4V_d}{\pi h}\,|\cos(h\pi/6)| = \sqrt{3}\left\{\frac{4}{\pi h}\frac{V_d}{2}\right\} \text{ for } h = 6n \pm 1$$

Three-Phase Inverter Neutral Point Voltage





$$\begin{cases} v_{1-4} = v_{1-0} - v_{4-0} \\ v_{2-4} = v_{2-0} - v_{4-0} \\ v_{3-4} = v_{3-0} - v_{4-0} \end{cases} \rightarrow 3v_{4-0} = v_{1-0} - v_{1-4} + v_{2-0} - v_{2-4} + v_{3-0} - v_{3-4} =$$

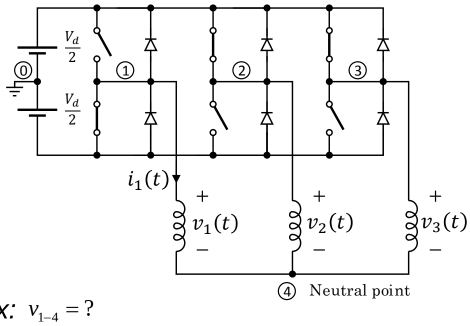
$$= v_{1-0} + v_{2-0} + v_{3-0} - \underbrace{(v_{1-4} + v_{2-4} + v_{3-4})}_{=0}$$

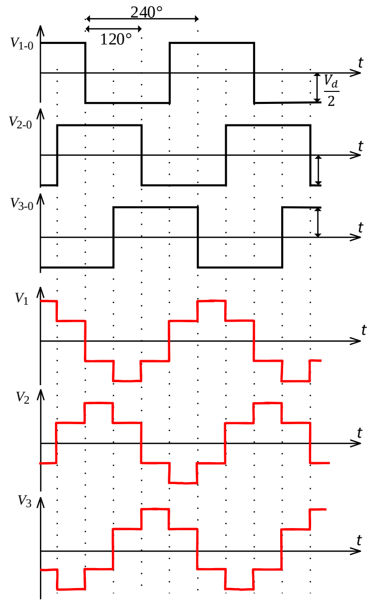
$$\Rightarrow 3v_{4-0} = v_{1-0} + v_{2-0} + v_{3-0}$$

$$v_{4-0} = \frac{1}{3}(v_{1-0} + v_{2-0} + v_{3-0})$$

Ex: $v_{4-0} = ?$

Three-Phase Inverter Phase Voltages



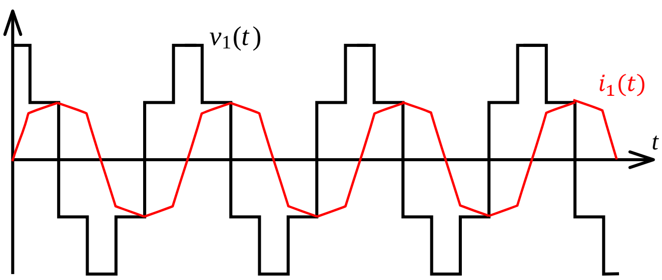


Ex: $v_{1-4} = ?$

$$v_{1-4} = v_{1-0} - v_{4-0}$$
$$= v_{1-0} - \frac{v_{1-0} + v_{2-0} + v_{3-0}}{3}$$
$$= \frac{2}{3} v_{1-0} - \frac{1}{3}(v_{2-0} + v_{3-0})$$

Three-Phase Inverter – Square Wave Operation With Inductive Load

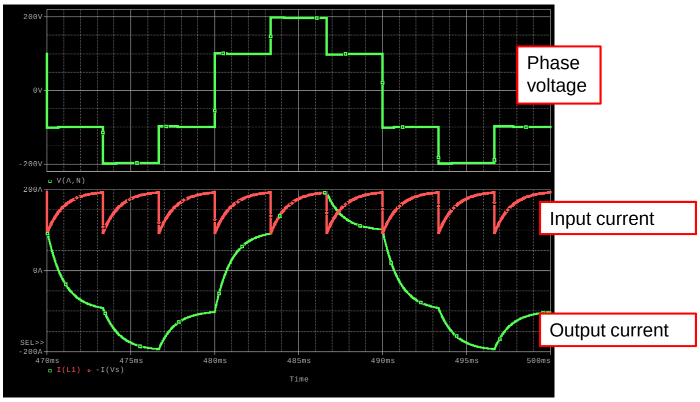
- By applying a constant voltage over the load, the current through the load will increase linearly
- The derivative depends on the applied voltage
- No active power is consumed due to the purely inductive load



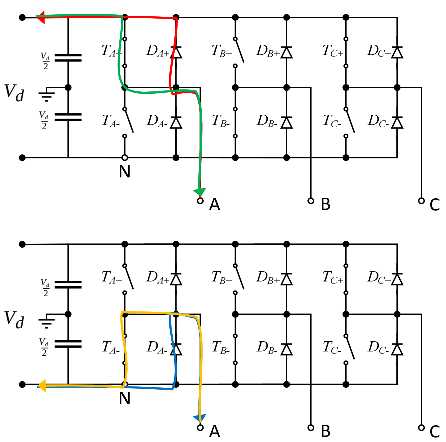
Ex: Can you predict the current plot?

Three-Phase Inverter – Square Wave Operation With RL-Load

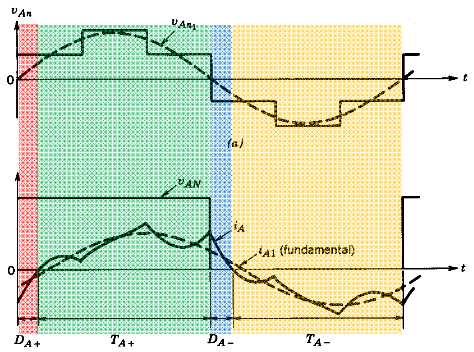
- If an RL-load is applied the source current will become positive and an active power will be consumed.



Three-Phase Inverter - Square-Wave Operation and Current Paths



$$v_{AB} = v_{AN} - v_{BN}$$



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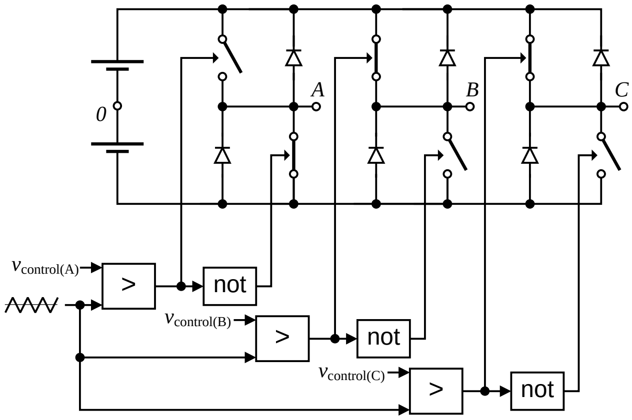
Ex: *Show current paths at various time intervals*

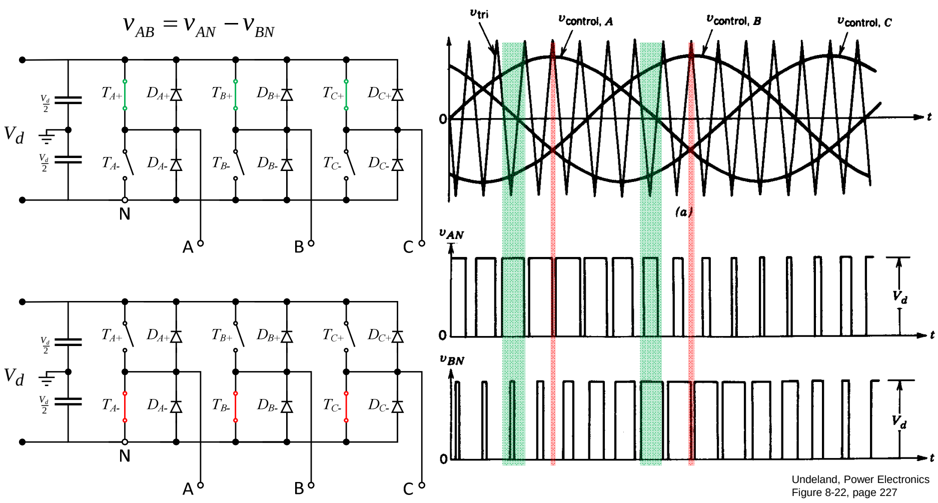
Three-Phase Inverter – PWM Operation

- Same triangular (carrier) wave is used for all three phases



Three-Phase Inverter PWM Operation

$$v_{AB} = v_{AN} - v_{BN}$$



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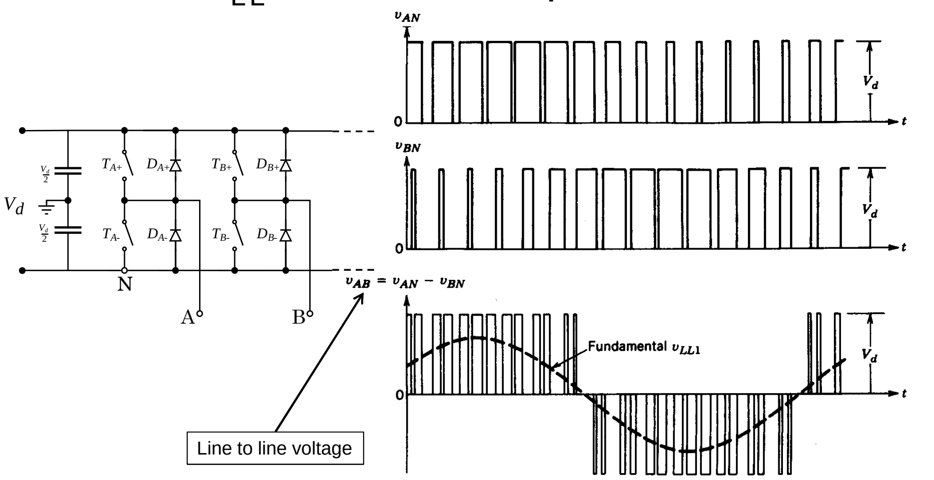
Three-Phase Inverter
V_{LL} and PWM Operation



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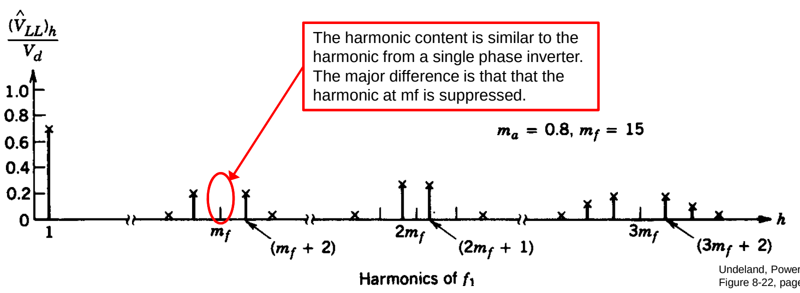
Three-Phase Inverter
Harmonics in PWM Operation

- The harmonics in the line-to-line voltage are of concern
- The harmonics at m_f are suppressed in three-phase



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Three-Phase Inverter
Harmonics in PWM Operation

Table 8-2 Generalized Harmonics of v_{LL} for a Large and Odd m_f That Is a Multiple of 3.

h \ m_a	0.2	0.4	0.6	0.8	1.0
1	0.122	0.245	0.367	0.490	0.612
$m_f \pm 2$	0.010	0.037	0.080	0.135	0.195
$m_f \pm 4$				0.005	0.011
$2m_f \pm 1$	0.116	0.200	0.227	0.192	0.111
$2m_f \pm 5$				0.008	0.020
$3m_f \pm 2$	0.027	0.085	0.124	0.108	0.038
$3m_f \pm 4$		0.007	0.029	0.064	0.096
$4m_f \pm 1$	0.100	0.096	0.005	0.064	0.042
$4m_f \pm 5$			0.021	0.051	0.073
$4m_f \pm 7$				0.010	0.030

Note: $(V_{LL})_h/V_d$ are tabulated as a function of m_a where $(V_{LL})_h$ are the rms values of the harmonic voltages.

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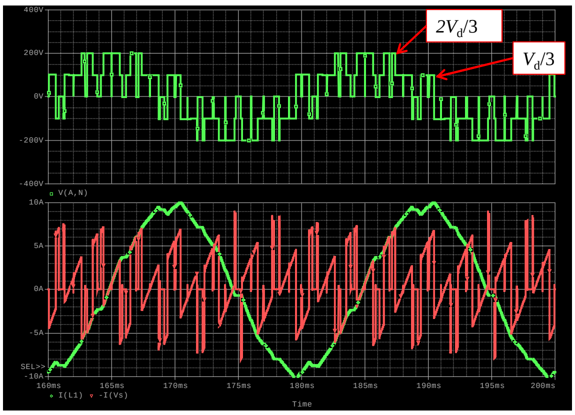
Three-Phase Inverter
PWM Operation With Inductive Load

- No active power is consumed due to the purely inductive load

$$v_{An} = \frac{2}{3} v_{AN} - \frac{1}{3}(v_{BN} + v_{CN})$$



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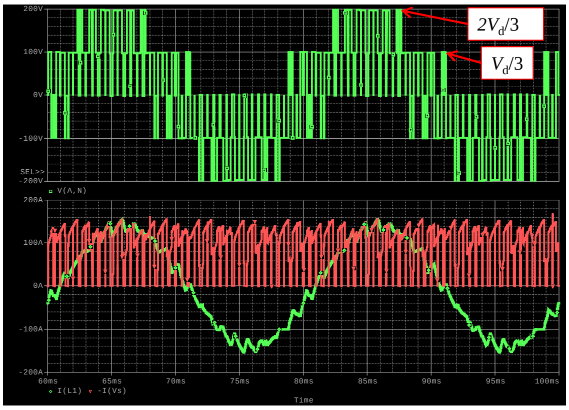
Three-Phase Inverter PWM Operation With RL-Load

- If an RL-load is applied the source current will become positive and an active power will be consumed.

$$v_{An} = \frac{2}{3} v_{AN} - \frac{1}{3}(v_{BN} + v_{CN})$$



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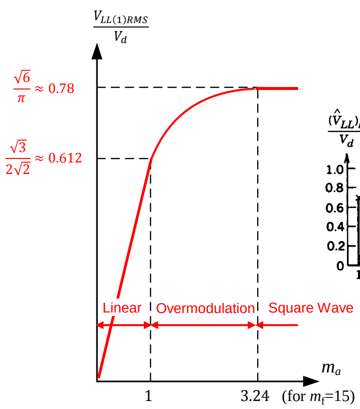
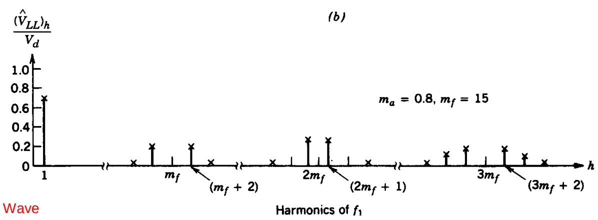
Three-Phase Inverter Modulation Ratio

- Linear relationship between the fundamental line-to-line voltage frequency component and the modulation index (m_a)





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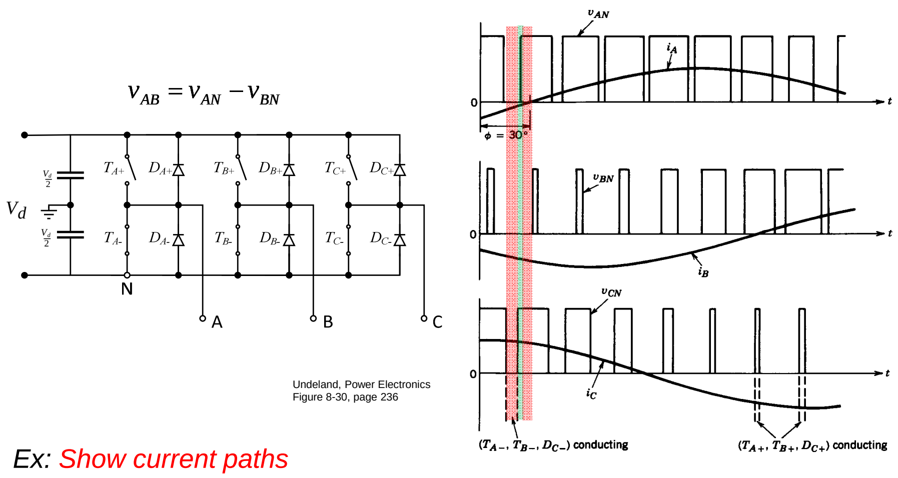
Three-Phase Inverter – PWM Operation and Current Paths



Ex: Show current paths

Three-Phase Inverter – Fundamental Frequency and Output Current Ripple

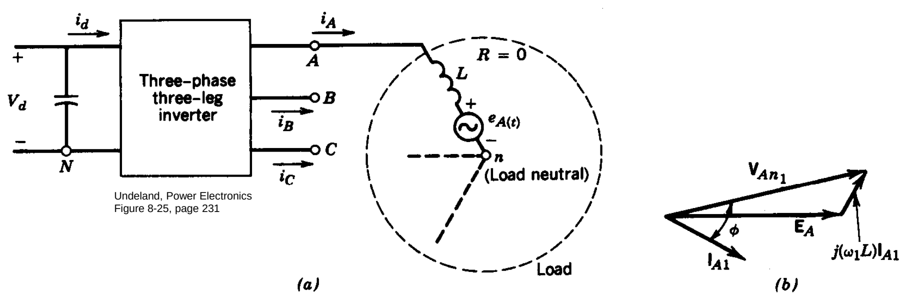


Figure 8-25 Three-phase inverter: (*a*) circuit diagram; (*b*) phasor diagram (fundamental frequency).

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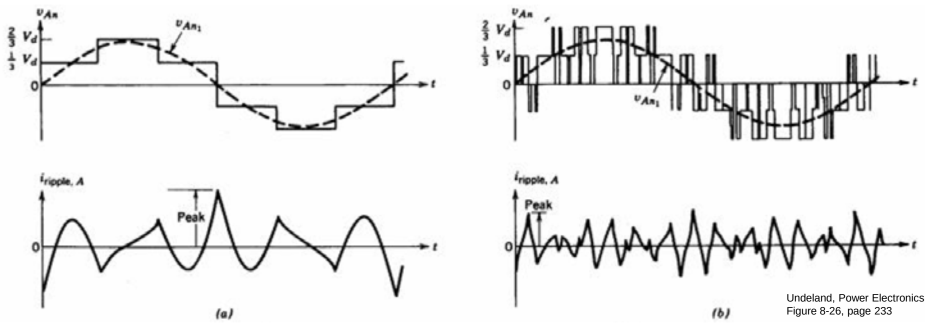
Three-Phase Inverter – Fundamental Frequency and Output Current Ripple



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- Square-wave mode
- PWM mode

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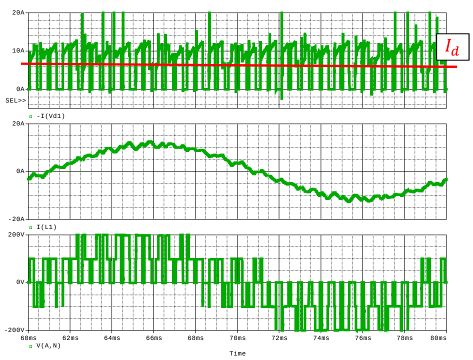
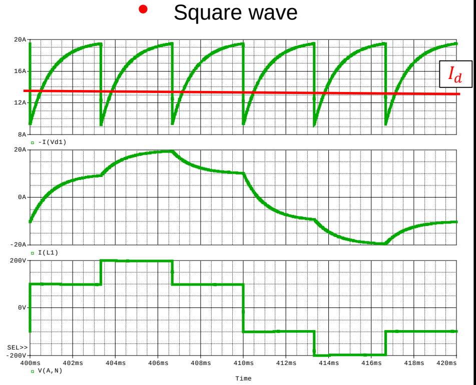
Three-Phase Inverter – DC-Side Current

- The current consists of a DC-component and harmonics related to the switching frequency

- PWM-mode



- Square wave



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Ex: can you compare to the single-phase case?

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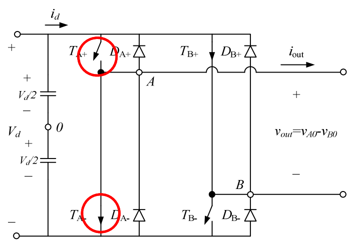
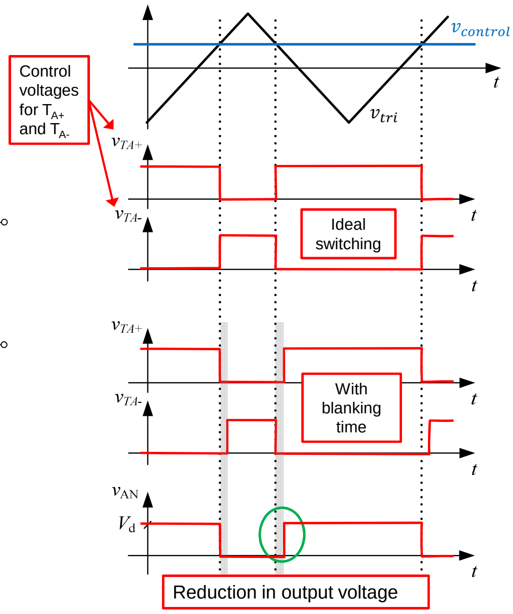
Blanking Time

- Positive output current





T_{A+} and T_{A-} can not be turned on at the same time, we need to apply a blanking time!

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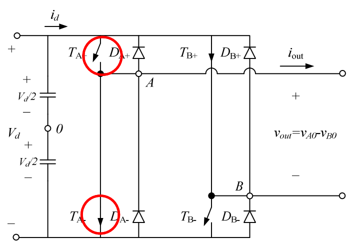
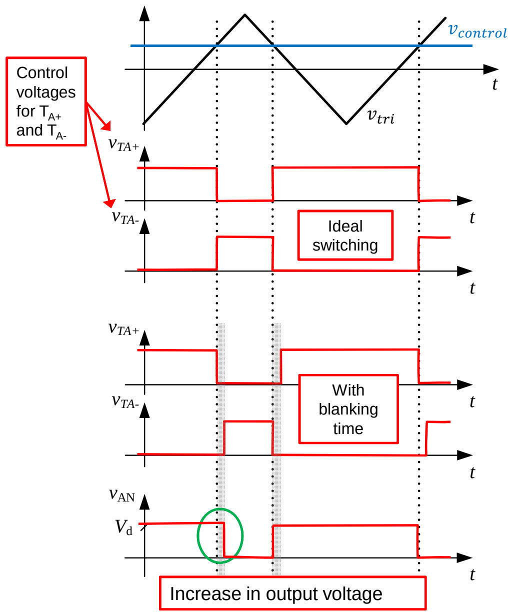
Blanking Time

- Negative output current

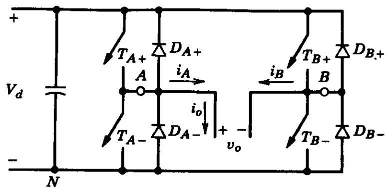




T_{A+} and T_{A-} can not be turned on at the same time, we need to apply a blanking time!

Effect of Blanking Time

- The output voltage will decrease or increase depending on the direction of the current.



$$\Delta V_o = \begin{cases} i_o > 0 \rightarrow \Delta V_{AN} - \Delta V_{BN} = +\dfrac{2t_\Delta}{T_s} V_d \\ i_o < 0 \rightarrow -\dfrac{2t_\Delta}{T_s} V_d \end{cases}$$

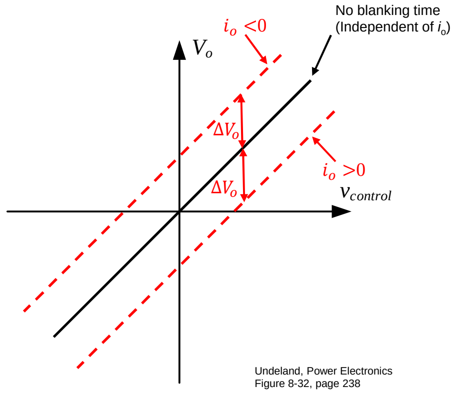


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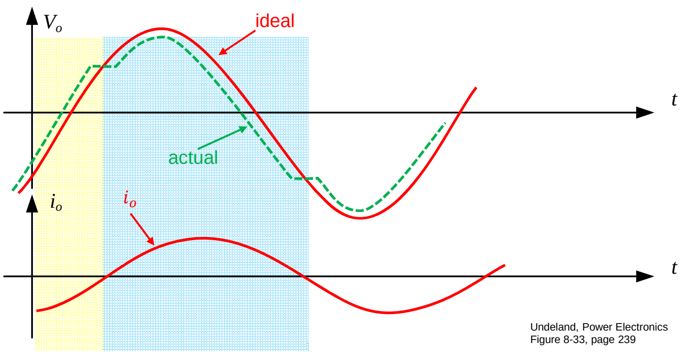
Figure 8-32, page 238

Effect of Blanking Time

- The average output voltage will either increase or decrease when the current changes polarity (zero crossing)
- The distortion at the zero crossings result in low order harmonics (third, fifth, seventh, …)



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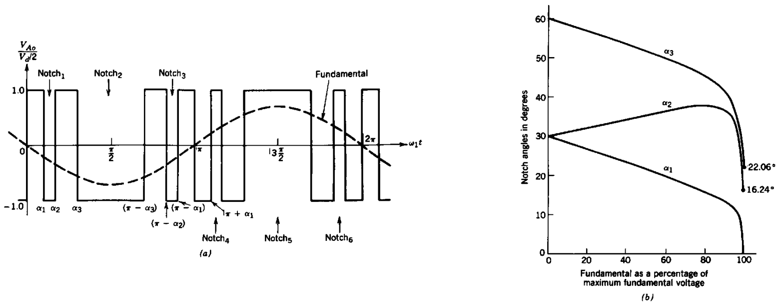
Other switching schemes
Harmonic elimination PWM

- Programmed switching to cancel certain harmonics (5th and 7th)



- The notch angles decided based on fundamental and harmonics to be cancelled

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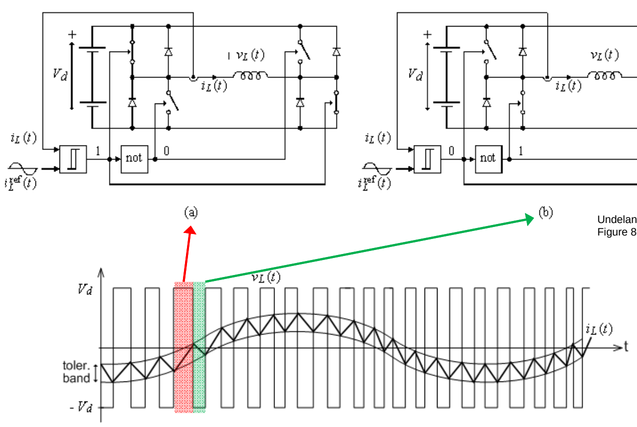
Other switching schemes
Tolerance-Band Current Control

- Simple algorithm used for direct torque control of machines



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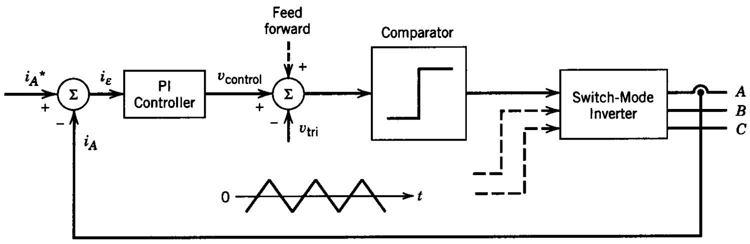
Other switching schemes
Fixed-frequency Current Control

- More accurate control possible (*dq*-control method) and the harmonic content can be predicted



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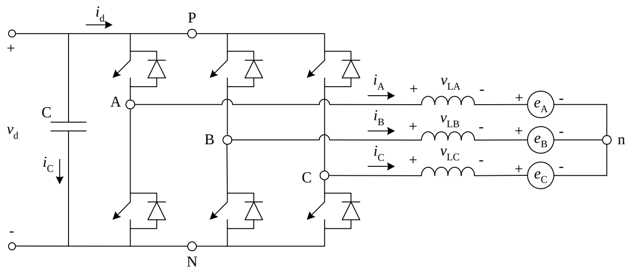
Tutorial 8



- Square: Assume $V_{LL(1)} = 200V$ the same as the back-emf voltage at a frequency of *52Hz* is as shown with $L = 100mH$. Calculate the peak ripple current.
- Square: With purely resistive load and no back-emf. Plot the waveform for i_d and $i_{A,B,C}$.
- Any guess how the waveforms behave for a PWM case?

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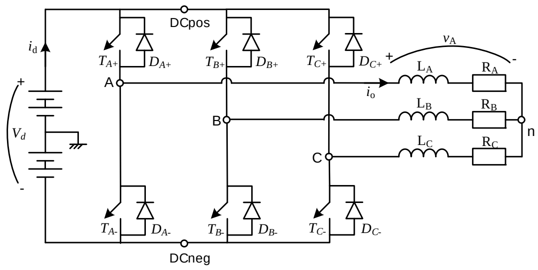
PSpice 5



Square-wave vs PWM for operation

- Load voltage, load current and neutral voltage waveforms
- I_d waveform for inductive and resistive loads
- Impact of back-emf angle on the output and dc current waveforms

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Summary

- Basic operating principle of a three-phase inverter
- Comparison of square-wave operation vs. PWM switching strategy
- Comparison of output ripple current in single- and three-phase inverters
- What are the Impacts of blanking time in switching?
- Review of alternative switching strategies in inverters
- Learning outcome:
  - Operating principles of a three-phase DC/AC inverter with different modulation strategies (e.g. PWM and square wave operation).