Power Quality Notes 2-1 (MT)

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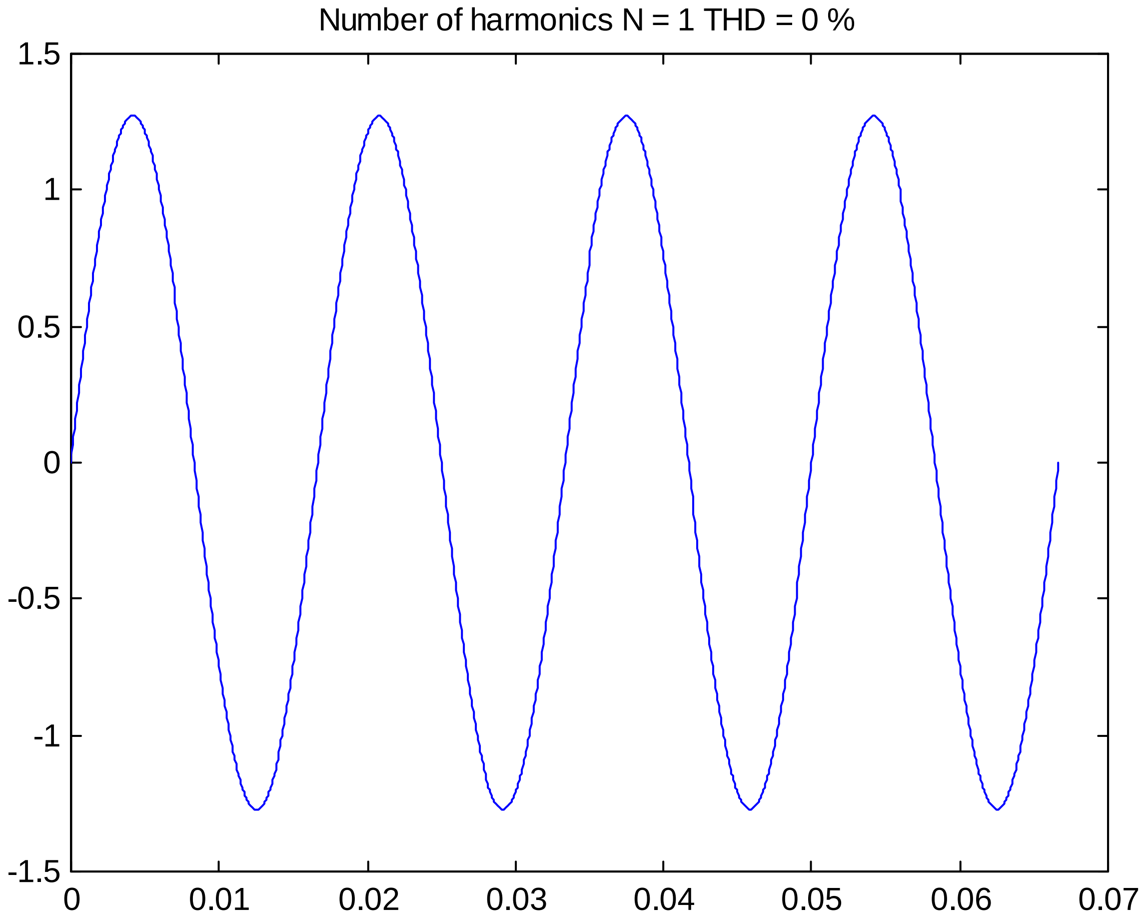
Class #2 - Hour #1 (4/12/05) Harmonic Current Sources

- Some more definitions
  - Crest factor
  - THD
- Single-phase rectifiers
  - Inductor filter
  - Capacitor filter
- Three-phase rectifiers
  - Inductor filter
  - Harmonics

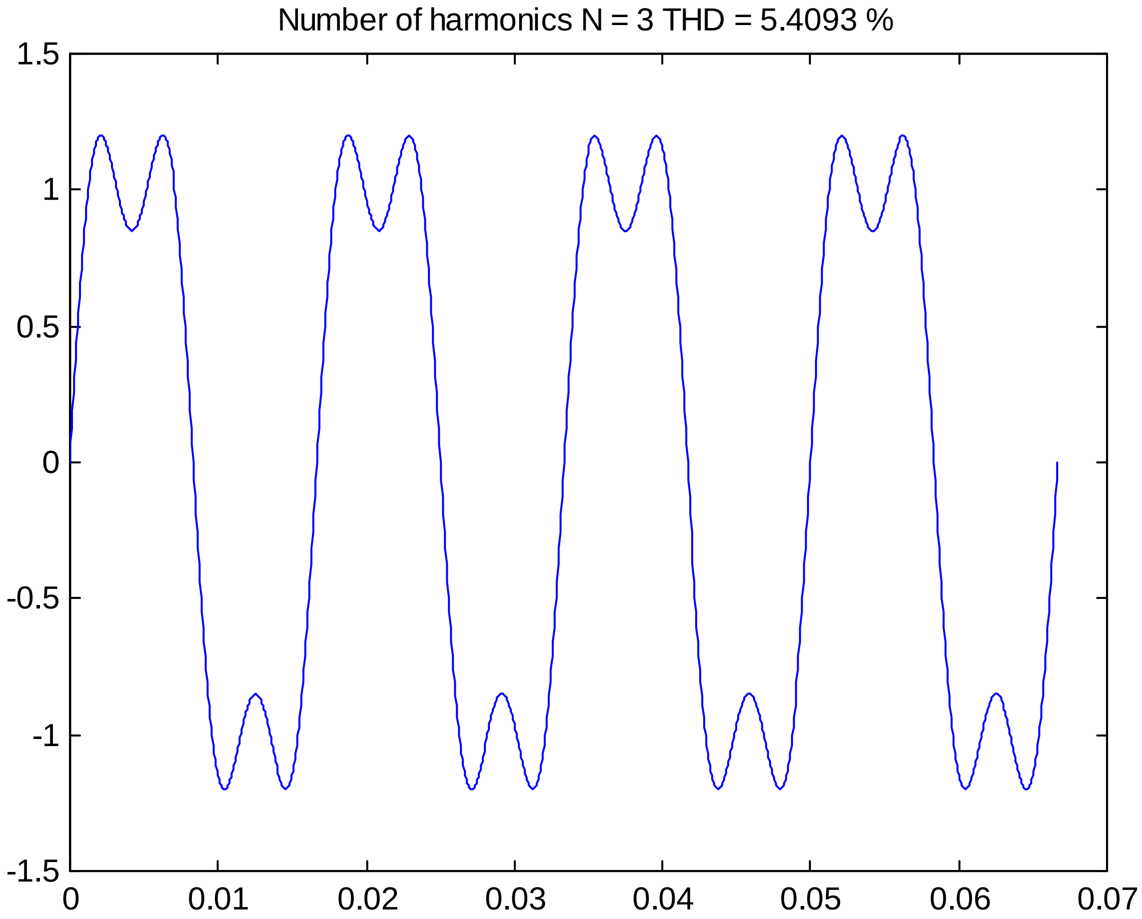
Crest Factor

- Ratio of peak value to RMS value
- For a sinewave, crest factor = 1.4
  - Peak = 1; RMS = 0.707
- For a square wave, crest factor = 1
  - Peak = 1; RMS = 1

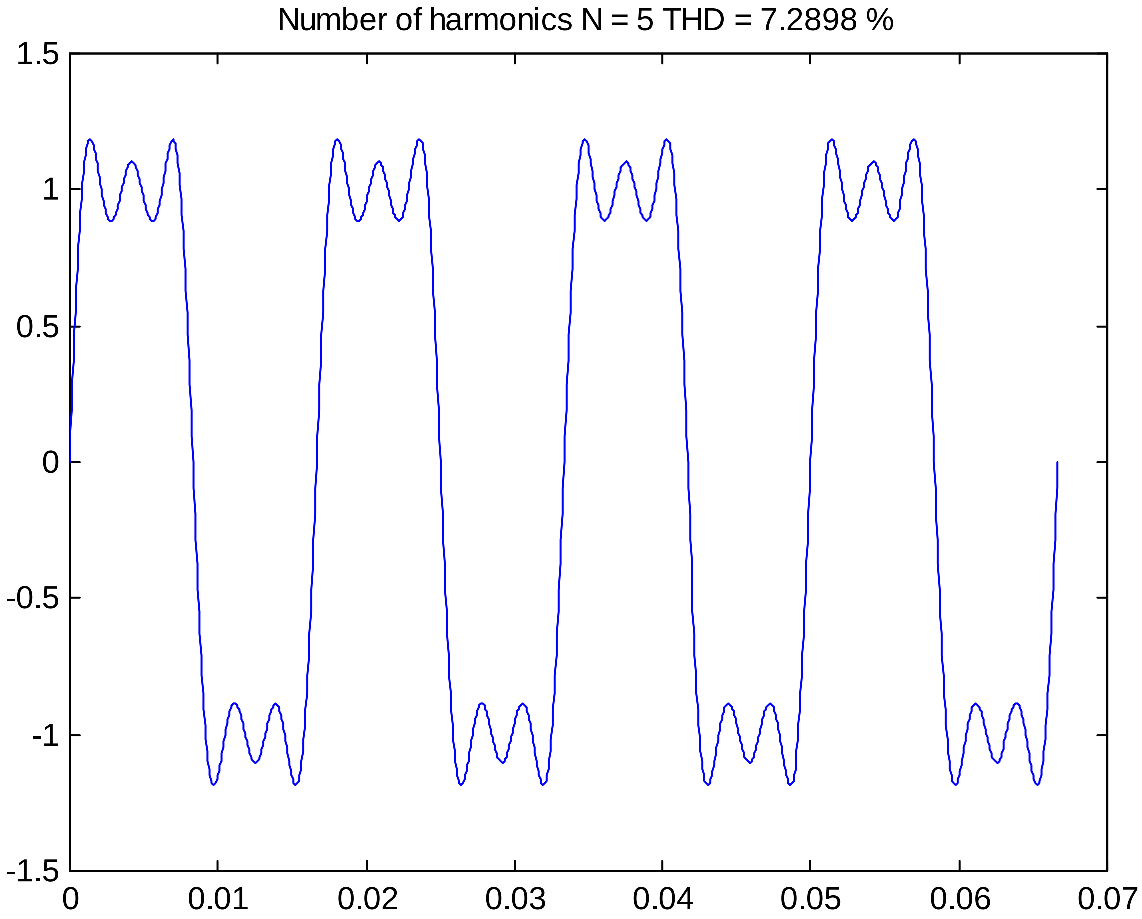
Harmonics and THD - Sinewave



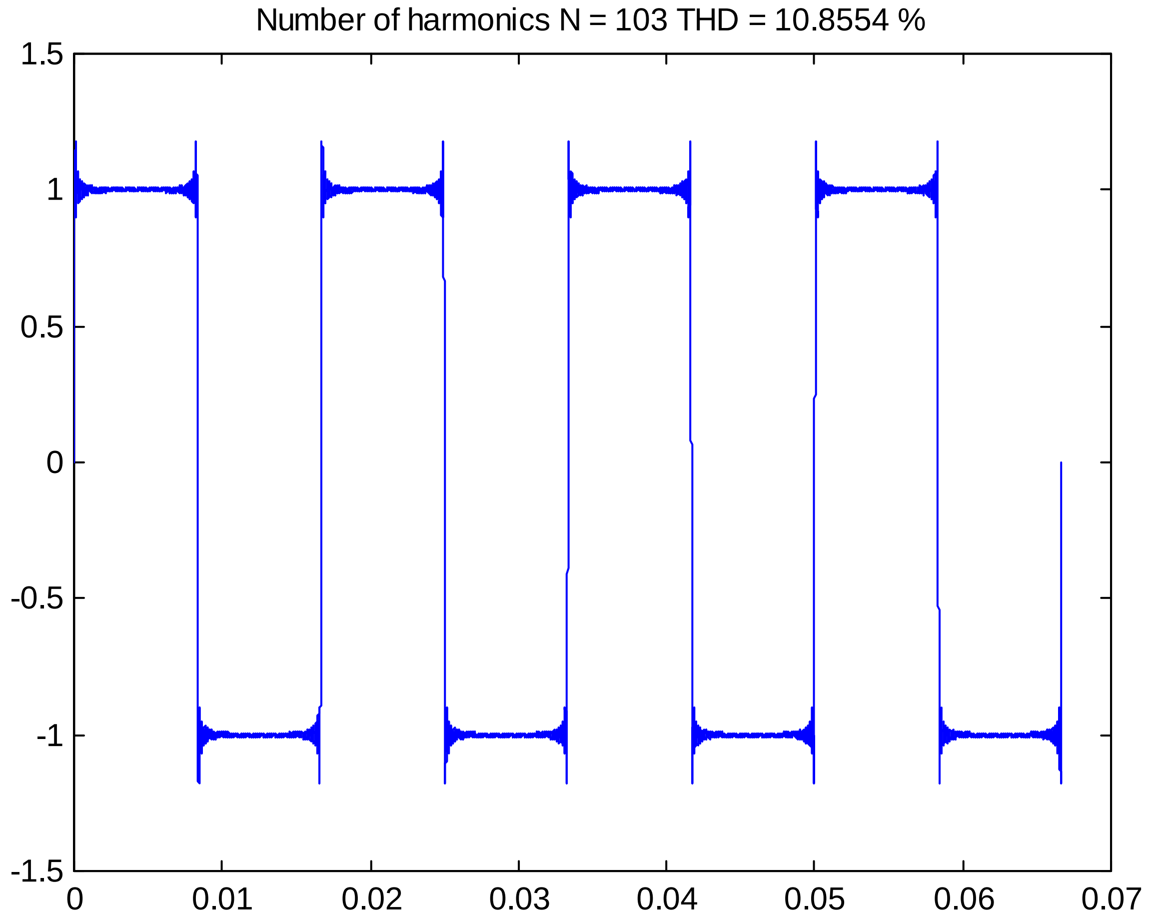
Harmonics and THD - Sinewave + 3rd Harmonic



Harmonics and THD --- Sinewave + 3rd + 5th Harmonic



Harmonics and THD - Up to N = 103



Half-Wave Rectifier, Resistive Load

- Simplest, cheapest rectifier
- Line current has DC component; this current appears in neutral
- High harmonic content, Power factor = 0.7

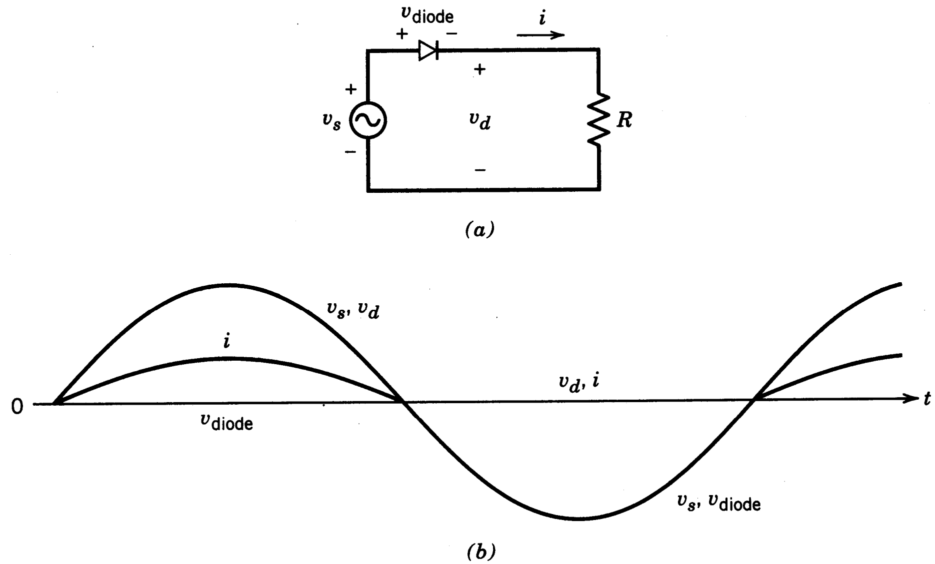
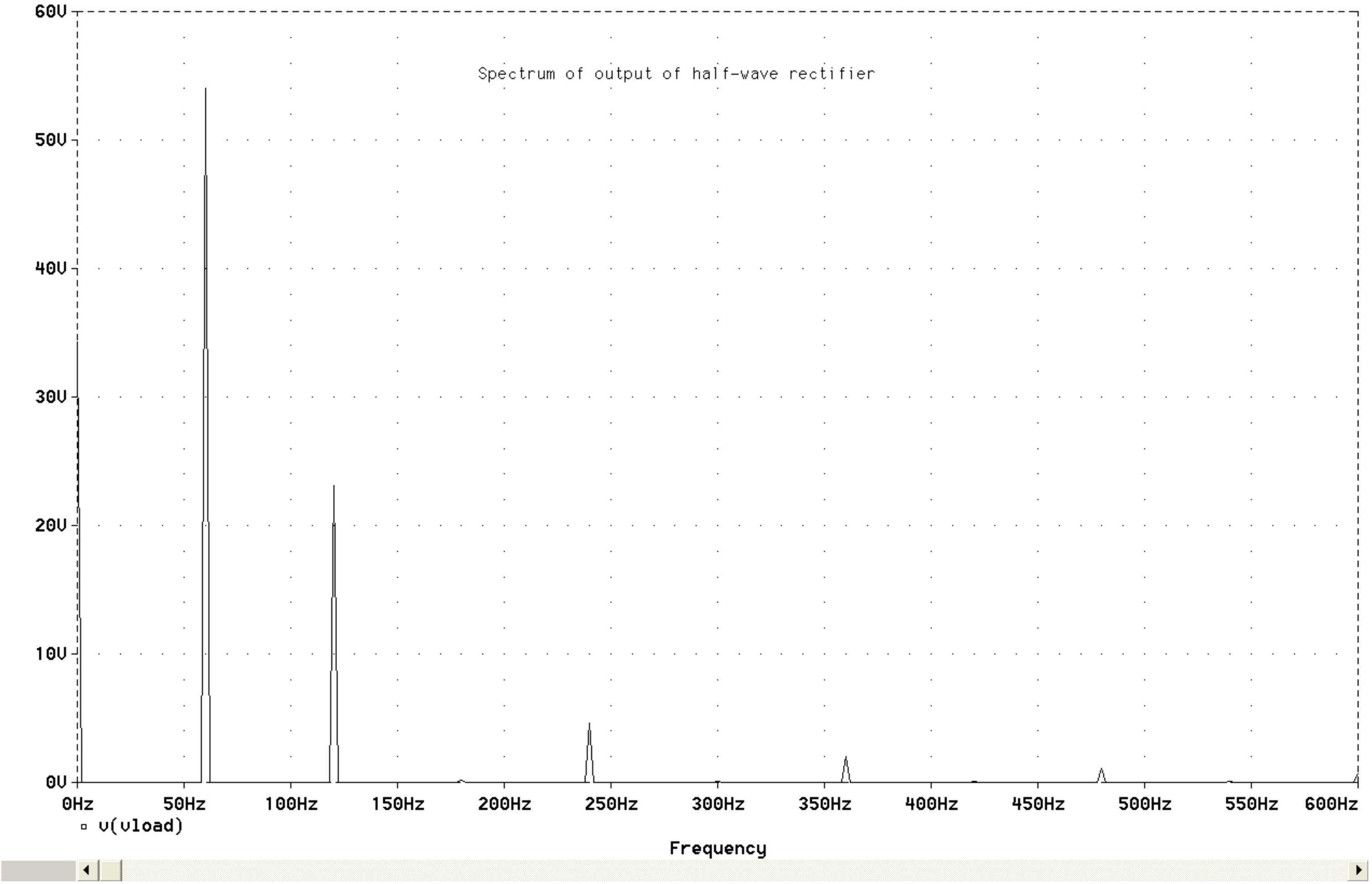


Figure 5-2 Basic rectifier with a load resistance.

$$P.F. = \frac{P_{avg}}{V_{RMS} I_{RMS}}$$

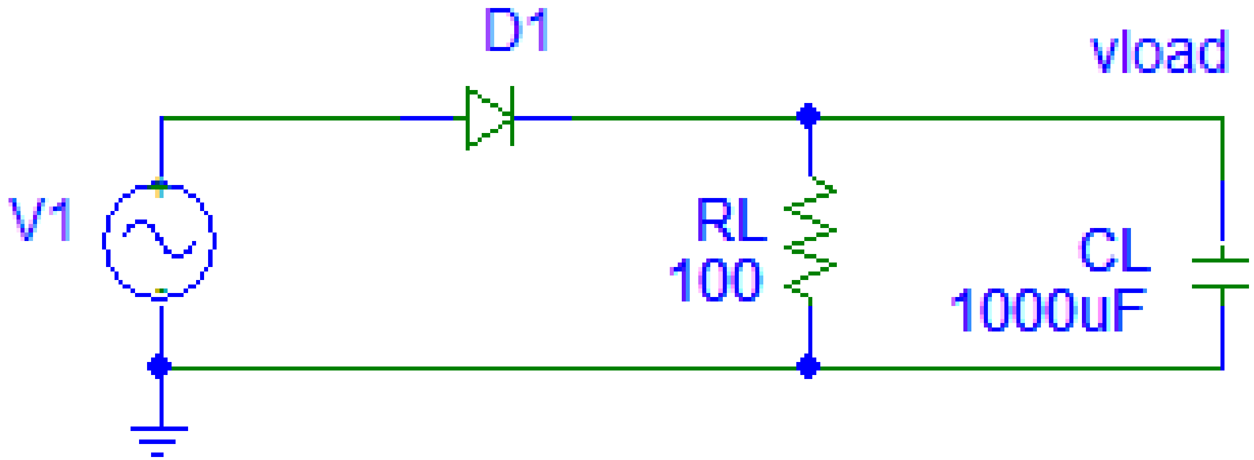
Reference: Mohan, Undeland and Robbins, Power Electronics, Converters, Applications and Design, John Wiley, 2003, pp. 80

Half-Wave Rectifier, Resistive Load --- Spectrum of Load Voltage



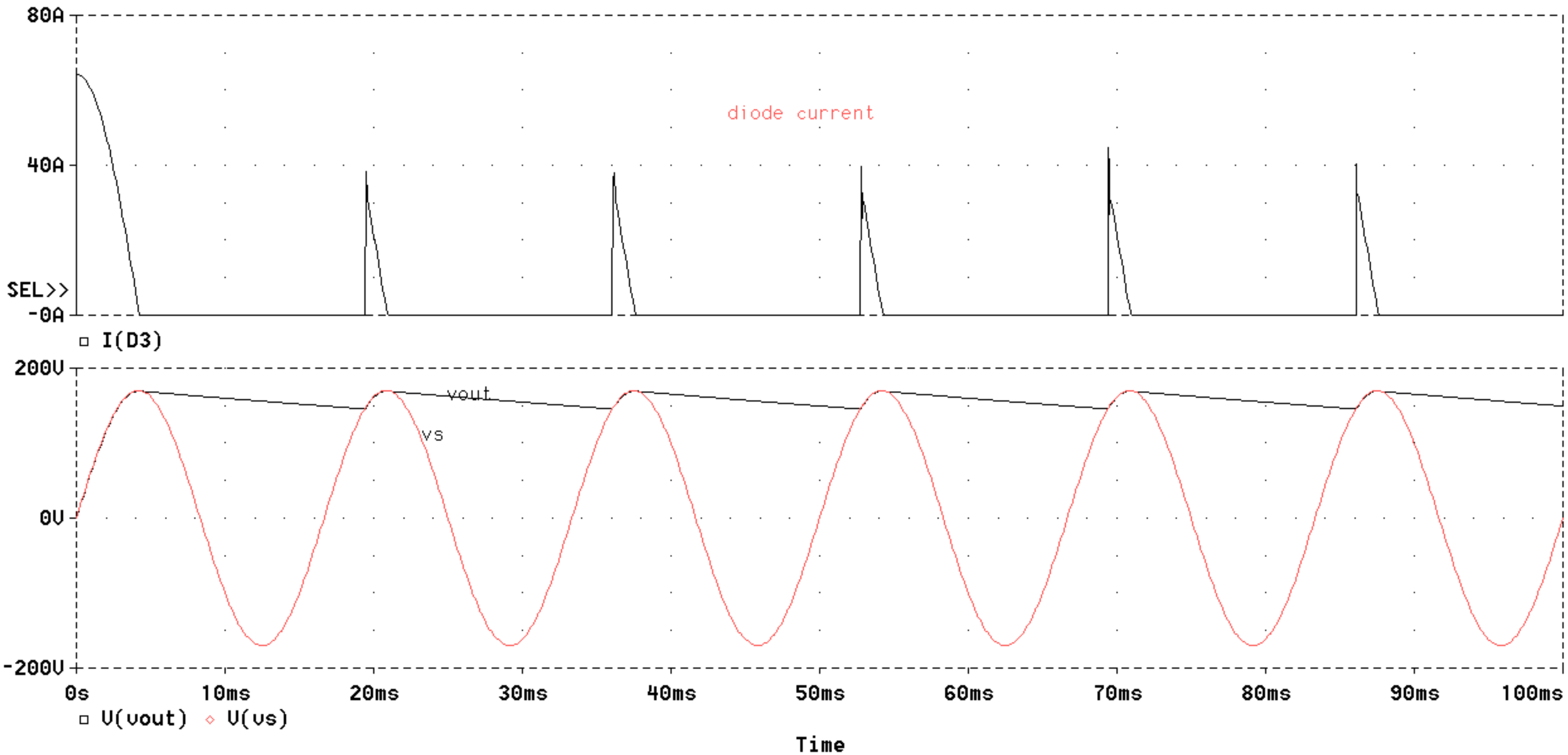
Half Wave Rectifier with RC Load

- More practical rectifier
- For large RC, this behaves like a peak detector

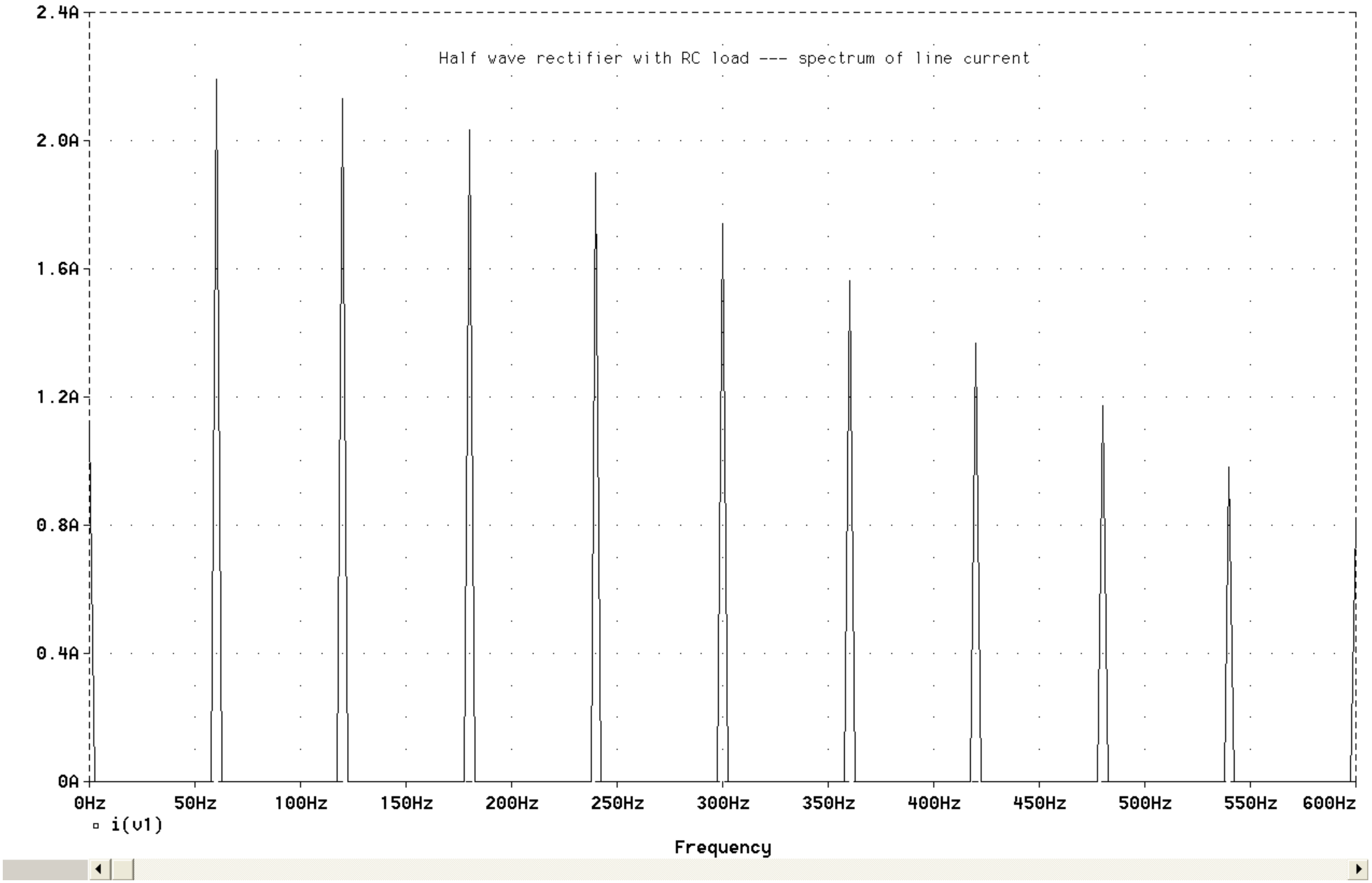


Half Wave Rectifier with RC Load

- Note poor power factor due to peaky line current
- Note DC component of line current



Half Wave Rectifier with RC Load --- Spectrum of Line Current



Single-Phase Full-Wave Rectifier

- Large capacitor at the dc output for filtering and energy storage
- L_s models inductance of power line

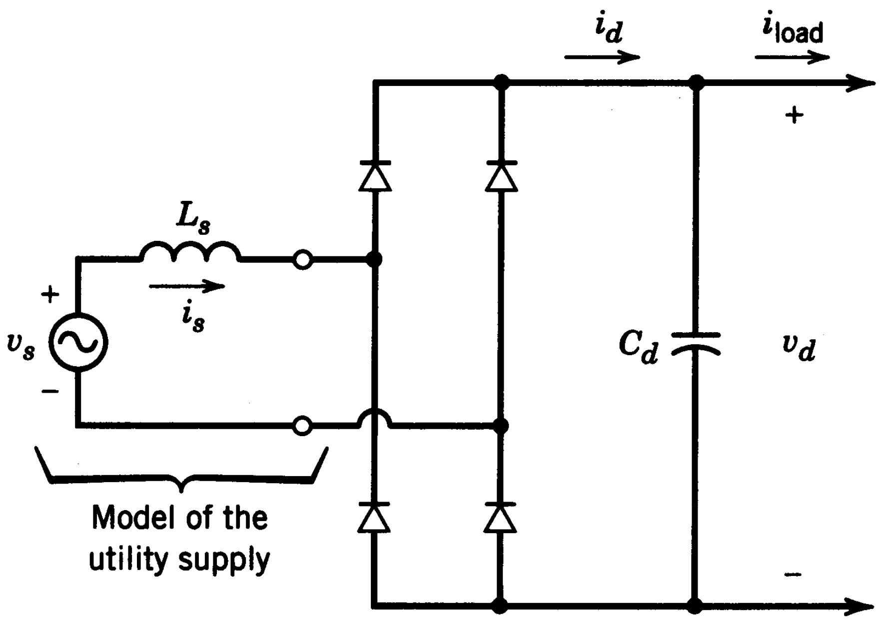


Figure 5-5 Single-phase diode bridge rectifier.

Reference: Mohan, Undeland and Robbins, Power Electronics, Converters, Applications and Design, John Wiley, 2003, pp. 83

Comments on Line Impedance

- Very roughly, line inductance is ~1 microHenry per meter of wire length
  - We can calculate this in closed form for parallel-wire line, or for circular loop of round wire
- Wire DC resistance can be found from wire chart. E.g., #14 AWG is approximately 0.01Ω/meter at 75C

Full-Wave Diode Rectifier Analysis

- Two simple (idealized) cases to begin with
- Resistor load models unity power factor load
- I_d load models large inductive load

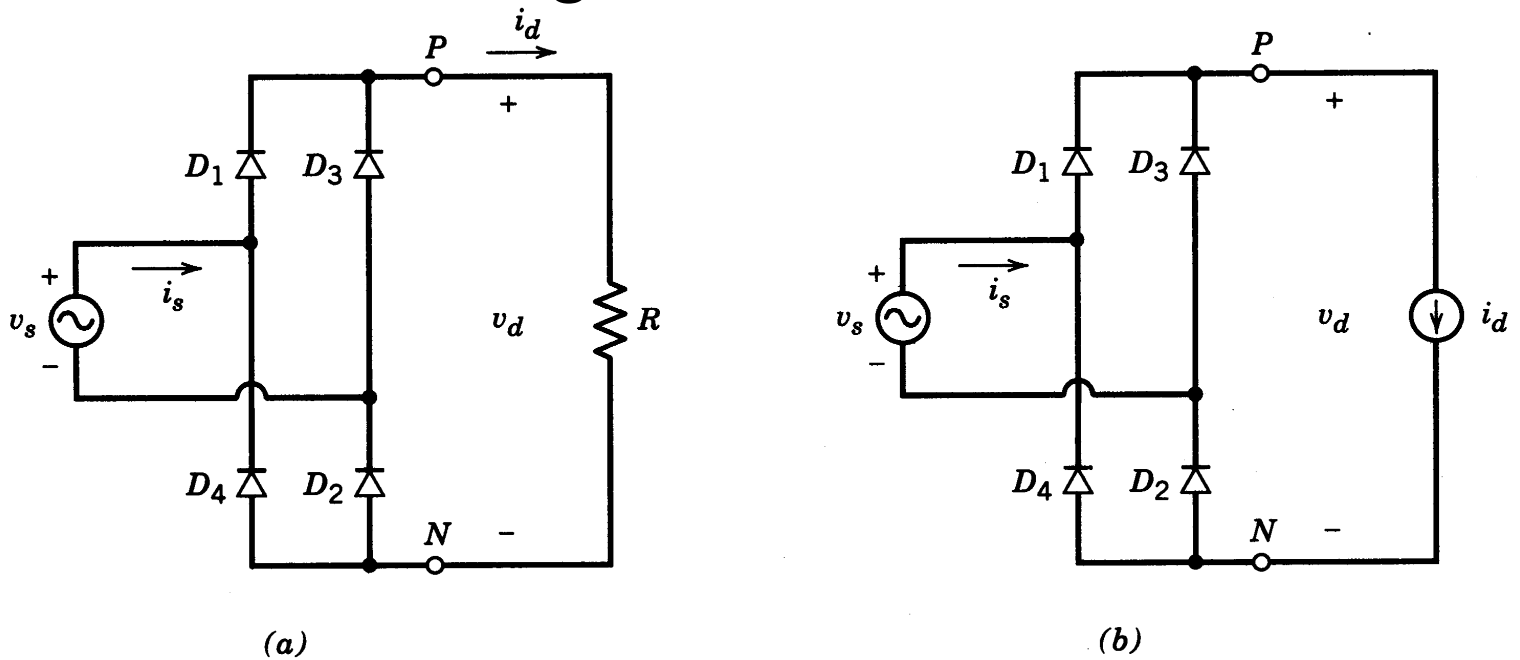
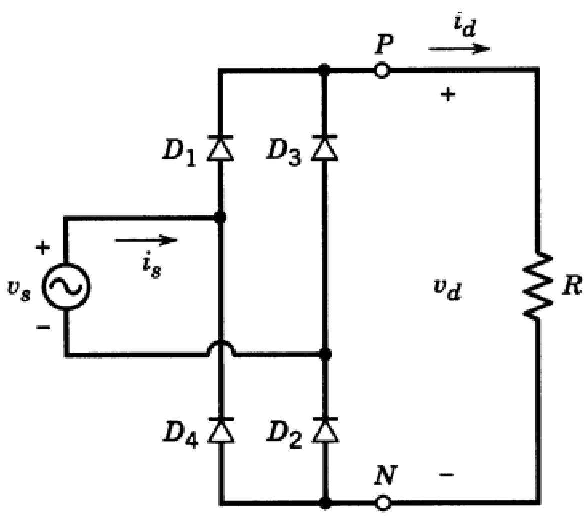


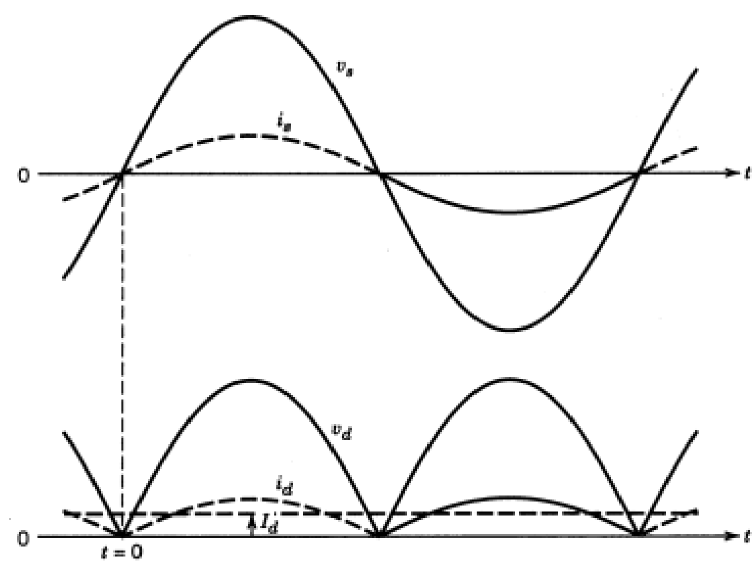
Figure 5-6 Idealized diode bridge rectifiers with $L_s = 0$.

Reference: Mohan, Undeland and Robbins, Power Electronics, Converters, Applications and Design, John Wiley, 2003, pp. 84

Diode-Rectifier Bridge Waveforms with Resistive Load

- Resistive load models high power factor load
- Note that the line current is in phase and has same shape as line voltage; hence PF = 1

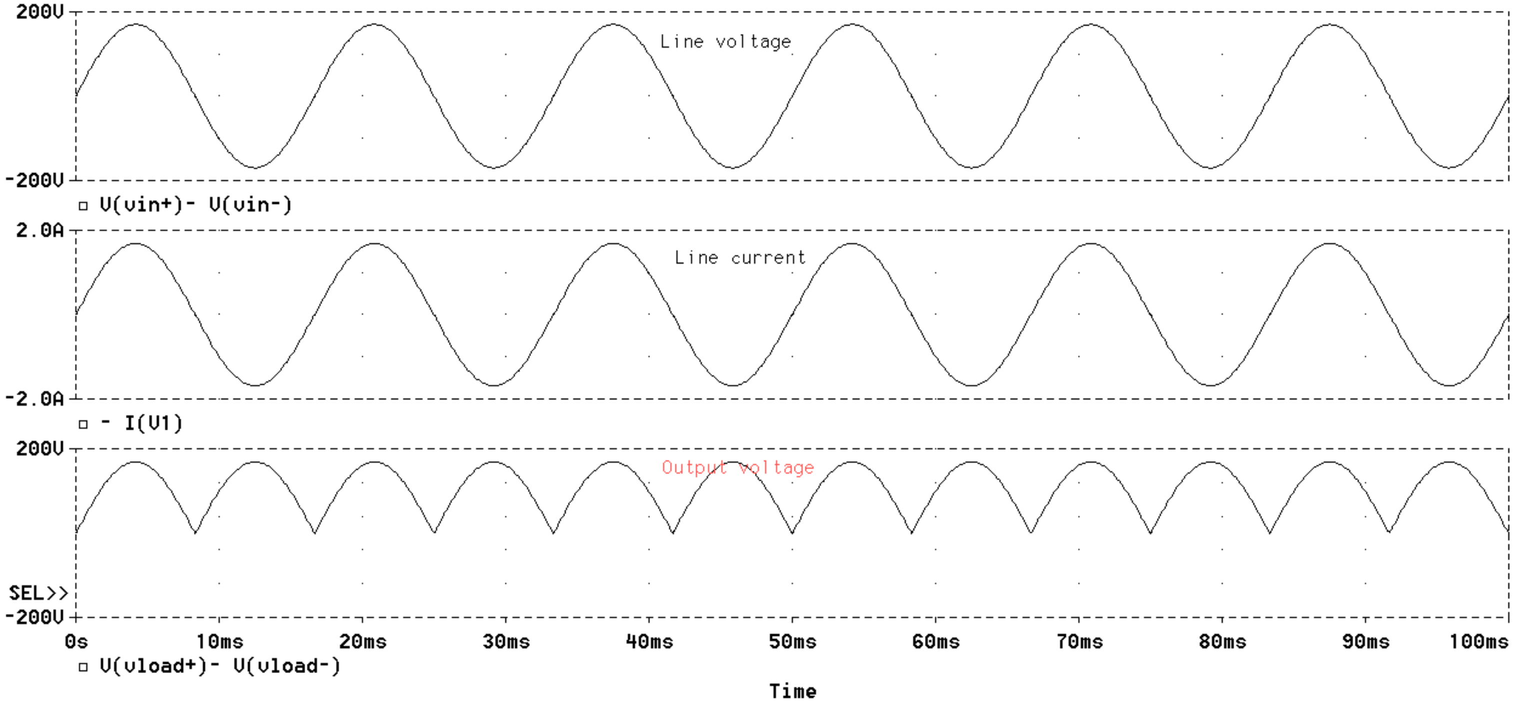




Reference: Mohan, Undeland and Robbins, <u>Power Electronics, Converters, Applications and Design</u>, John Wiley, 2003, pp. 84-85

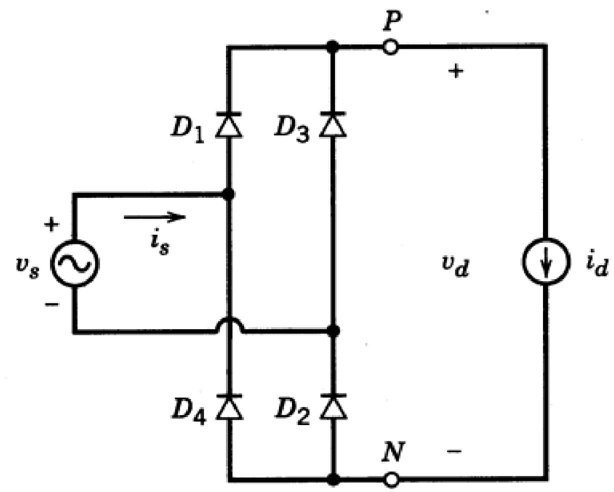
Single-Phase Full Wave Rectifier Bridge

- Only 2 diodes are on at any time
- Power factor = 1 (ignoring diode drops)
- Average value of output is 2x that of HWR



Diode-Rectifier Bridge Waveforms --- Large Inductive (~ Current Source) Load

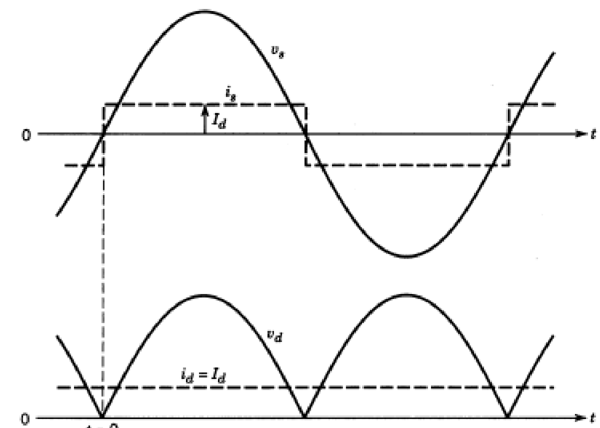
- Models case when L/R >> 1/120 Hz
- v_d waveform is the same as for a resistive load
- Power factor < 1



$$P_{avg} = V_{d,avg} I_{d,avg}$$

$$V_{d,avg} = \frac{1}{\pi}\int_0^{\pi} V_{pk}\sin(\omega t)d(\omega t) = \frac{2V_{pk}}{\pi}$$

$$PF = \frac{P_{avg}}{V_{RMS} I_{RMS}} = \frac{\left(\frac{2V_{pk}}{\pi}\right)\left(I_{d,avg}\right)}{\left(\frac{V_{pk}}{\sqrt{2}}\right)\left(I_{d,avg}\right)} = \frac{2\sqrt{2}}{\pi} \approx 0.9$$



Reference: Mohan, Undeland and Robbins, Power Electronics, Converters, Applications and Design, John Wiley, 2003, pp. 84-85

Diode-Rectifier Bridge Input Current

- Idealized case with a purely dc output current
- Harmonic distortion in line current results in PF < 1

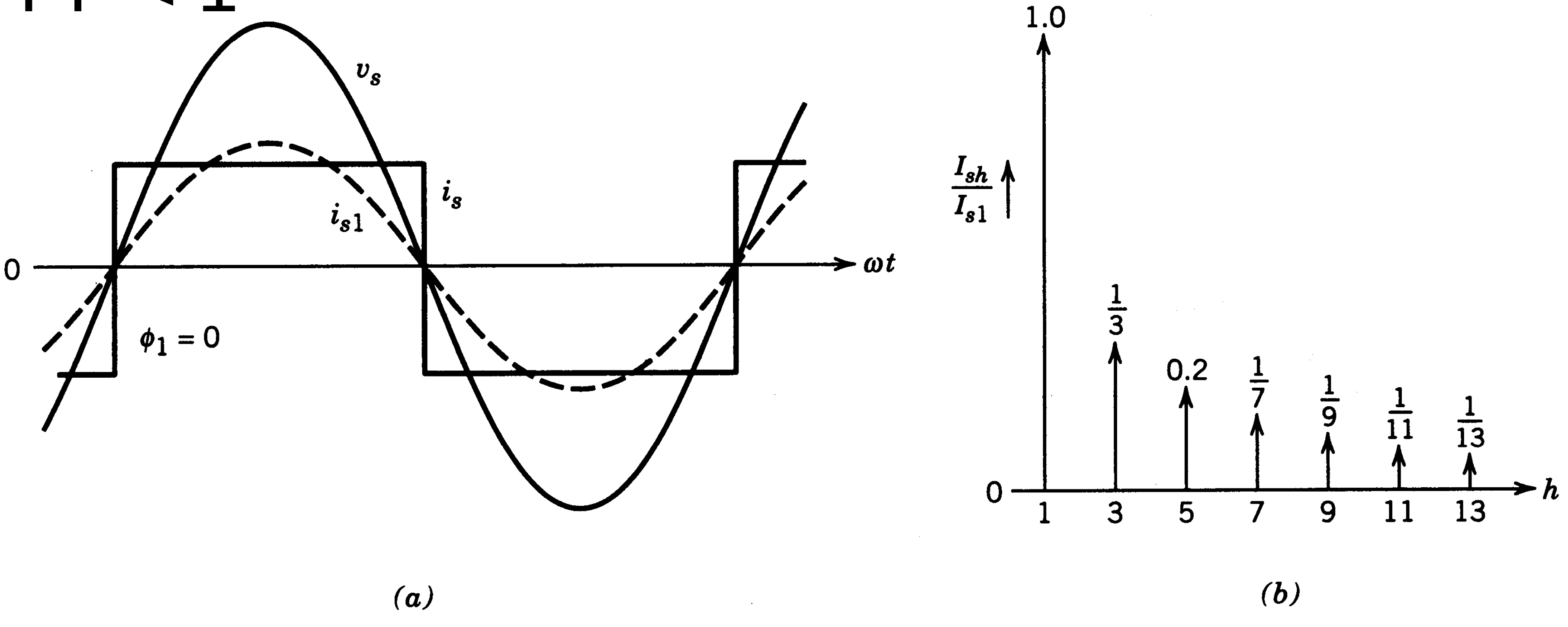


Figure 5-9 Line current i_s in the idealized case.

Reference: Mohan, Undeland and Robbins, *Power Electronics, Converters, Applications and Design*, John Wiley, 2003, pp. 86

Diode-Rectifier Bridge Analysis with AC-Side Inductance

- Output current is assumed to be purely DC; this models large inductive load
- Effect of line inductance: commutation and "softening" of line current

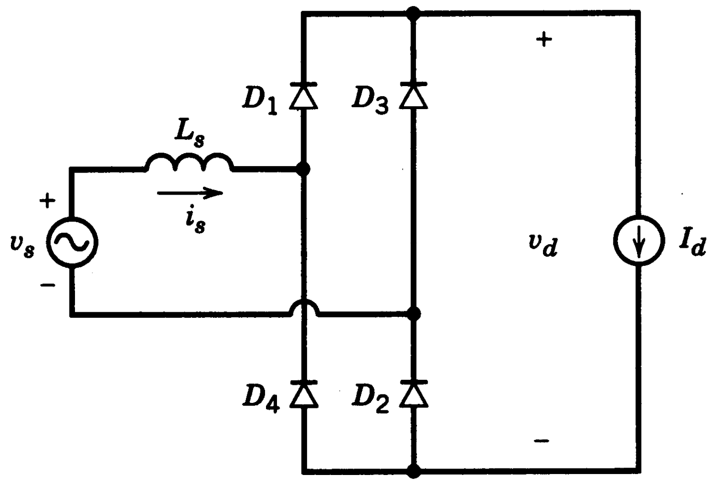
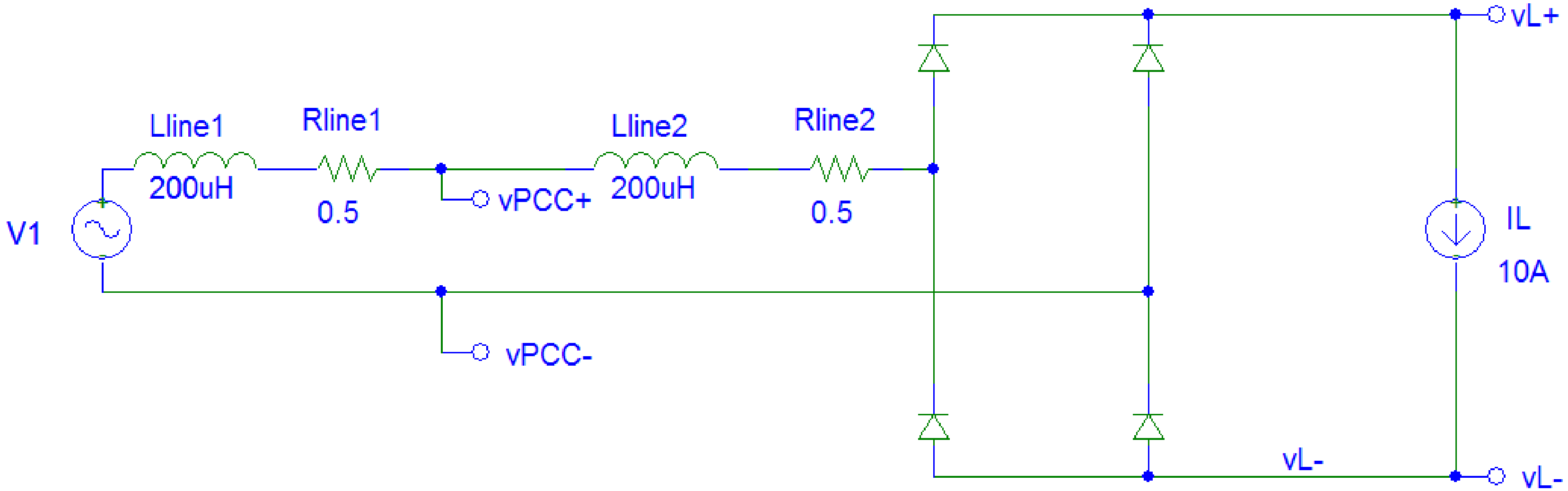


Figure 5-10 Single-phase rectifier with L_s.

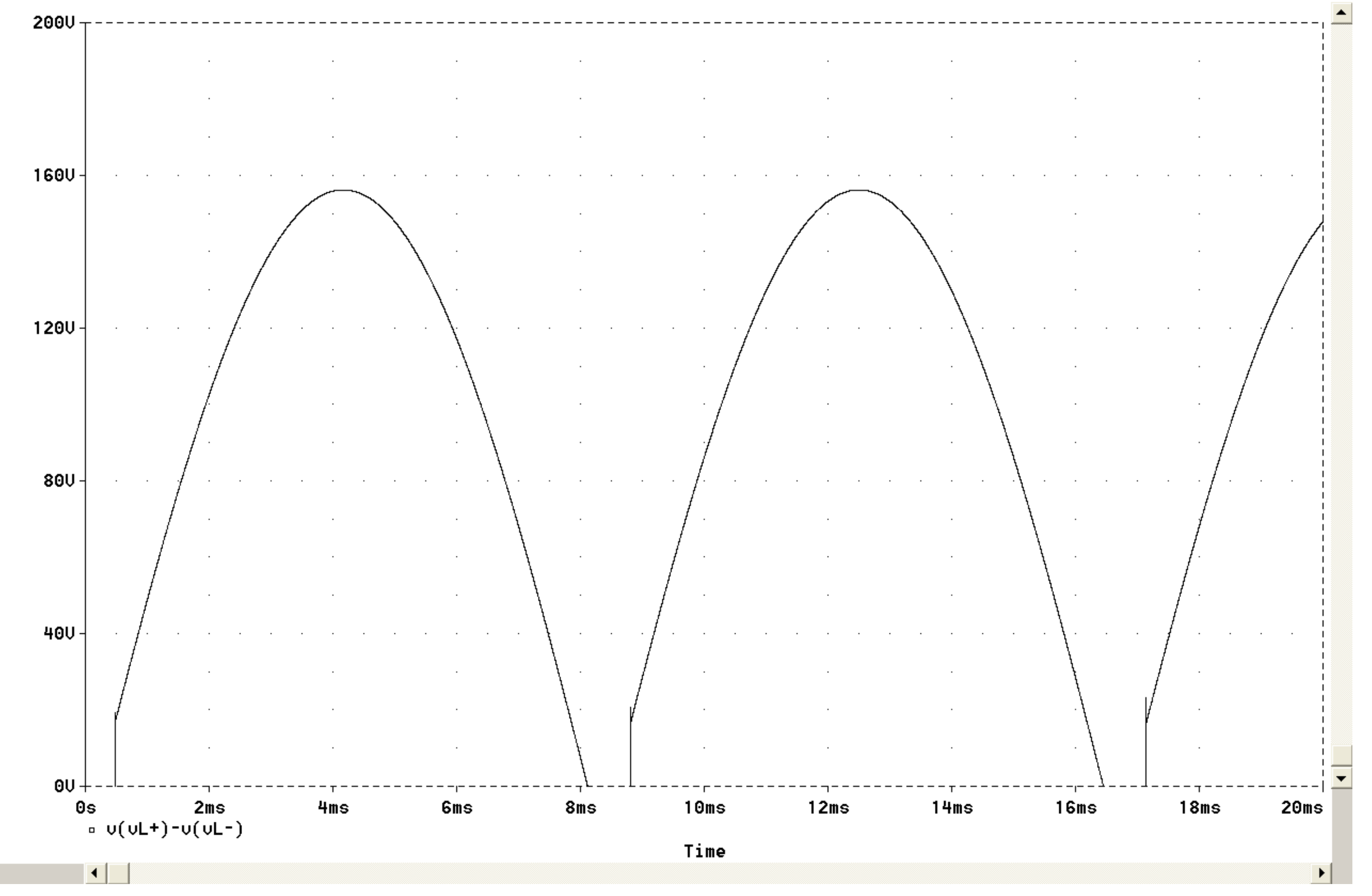
Reference: Mohan, Undeland and Robbins, Power Electronics, Converters, Applications and Design, John Wiley, 2003, pp. 87

Diode-Rectifier Bridge Analysis with AC-Side Inductance --- PSPICE Analysis

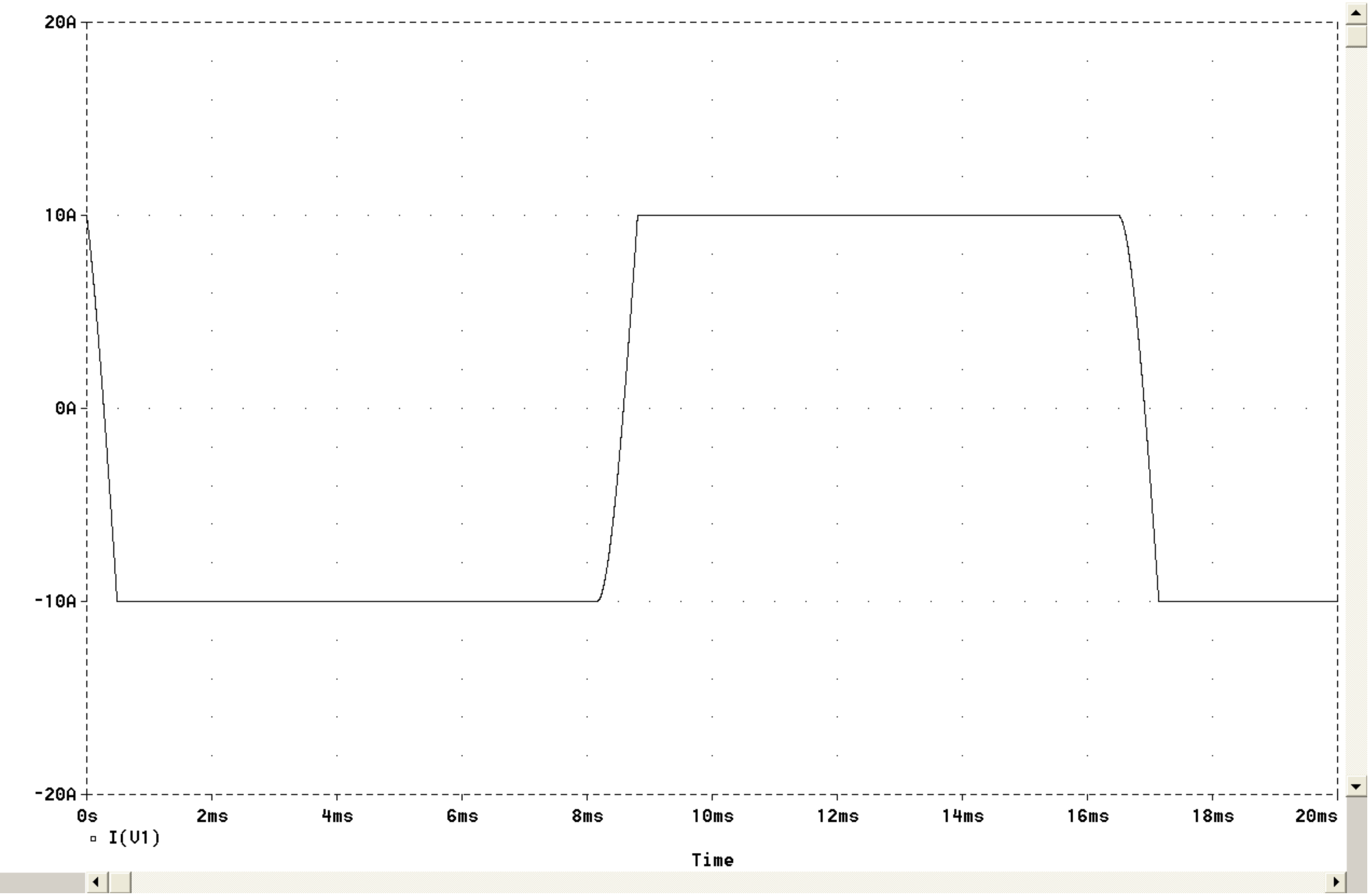
- Scenario: 400 meters of #8 AWG



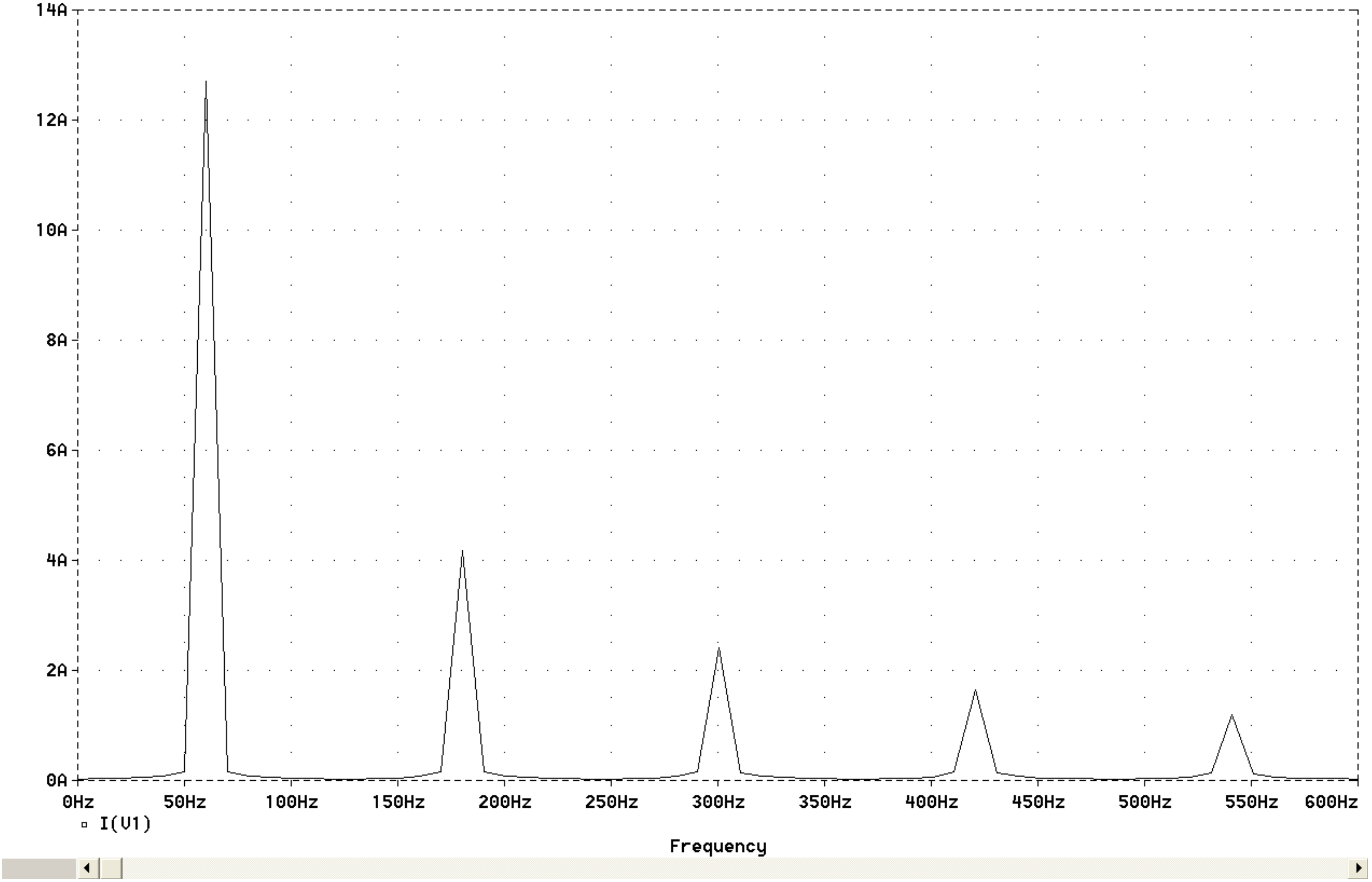
Diode-Rectifier Bridge Analysis with AC-Side Inductance --- Output Voltage



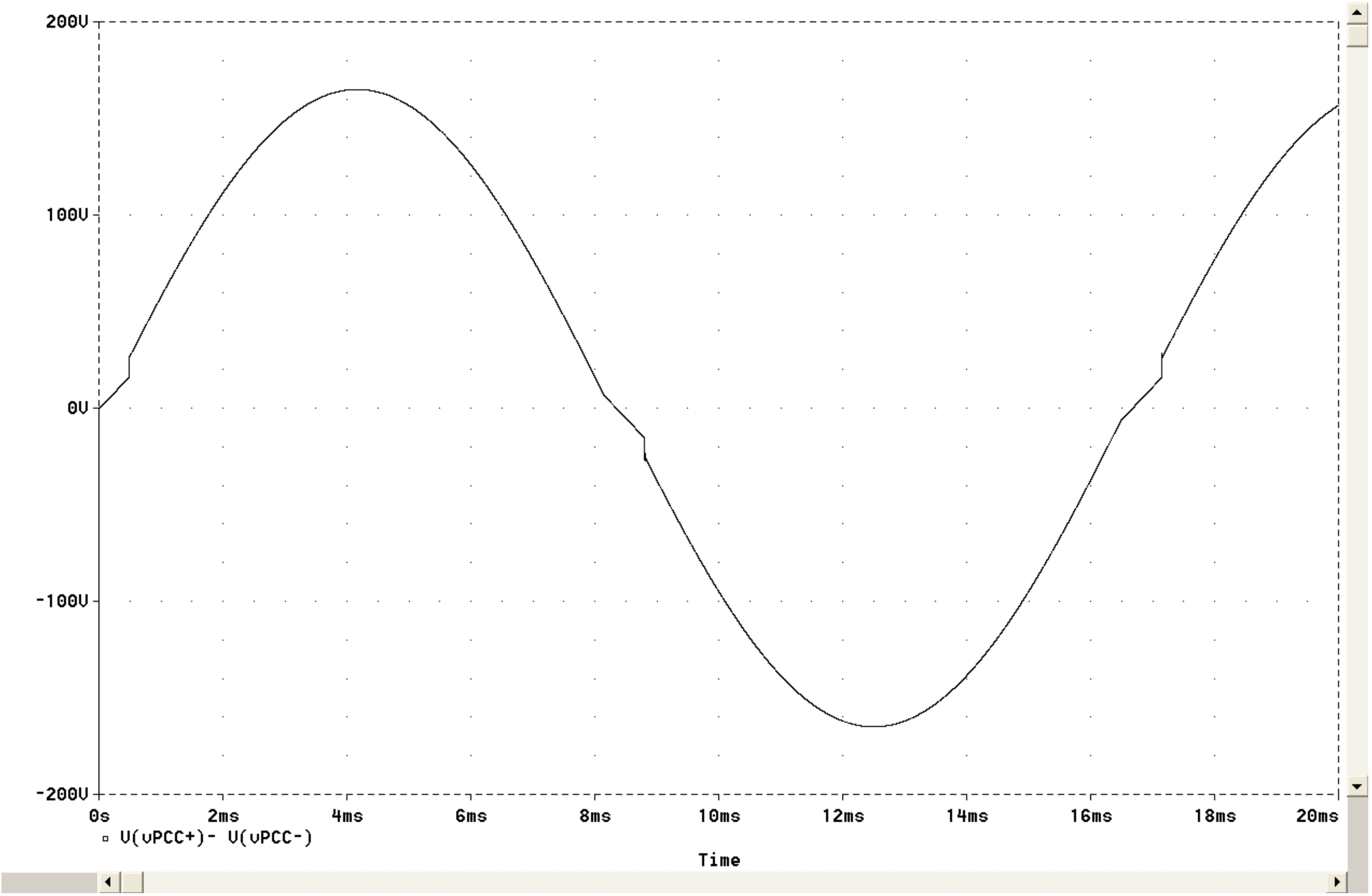
Diode-Rectifier Bridge Analysis with AC-Side Inductance --- Line Current



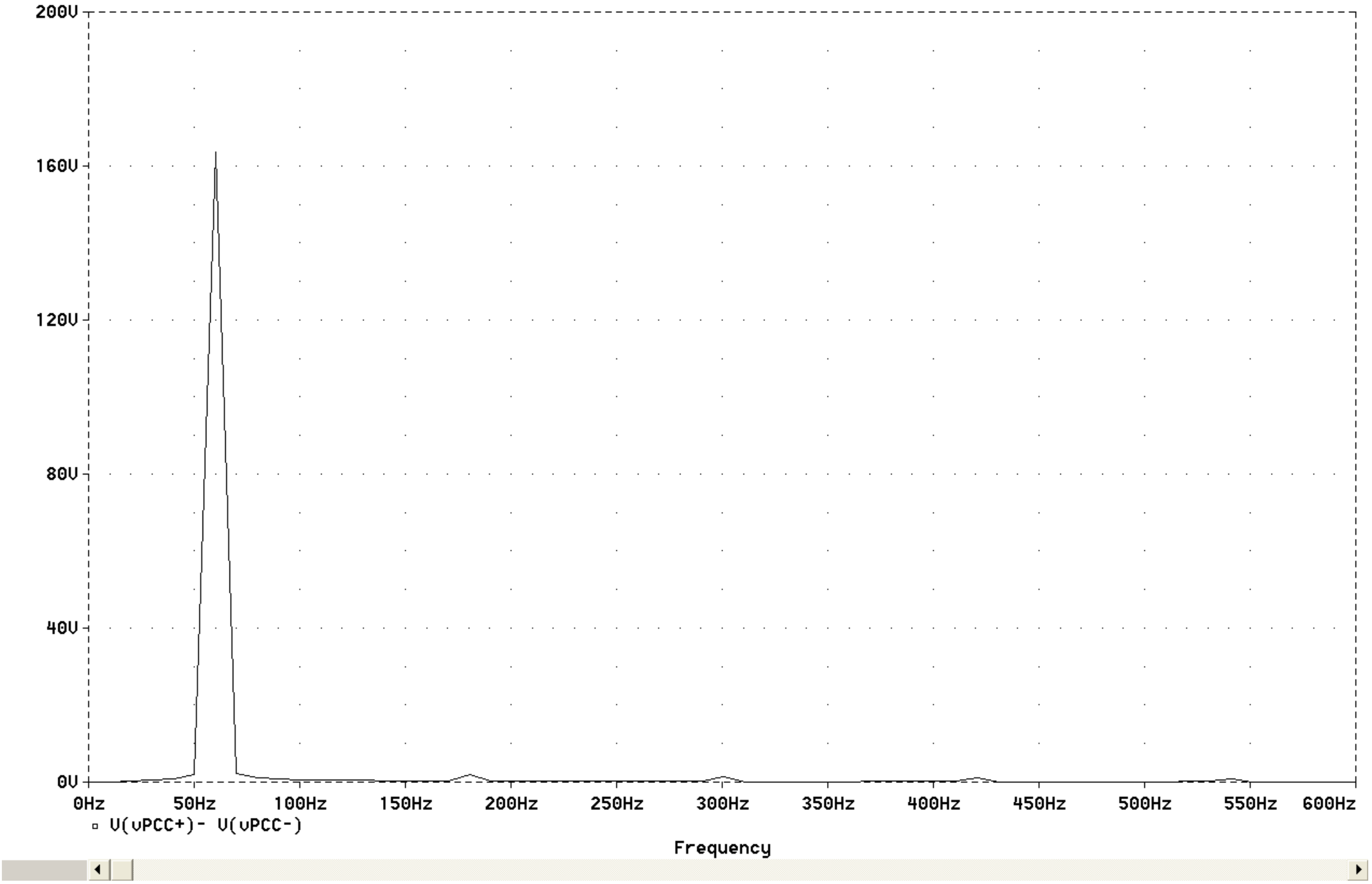
Diode-Rectifier Bridge with AC-Side Inductance --- Spectrum of Line Current



Diode-Rectifier Bridge with AC-Side Inductance --- Voltage at PCC



Diode-Rectifier Bridge with AC-Side Inductance --- Spectrum of Voltage at PCC



Understanding Current "Commutation"

- Commutation is process by which flowing current switches from one diode to the other
- With L_s=0, D1 and D2 snap ON and OFF infinitely fast
  - D1 is ON and D2 is OFF for positive half-cycle of line

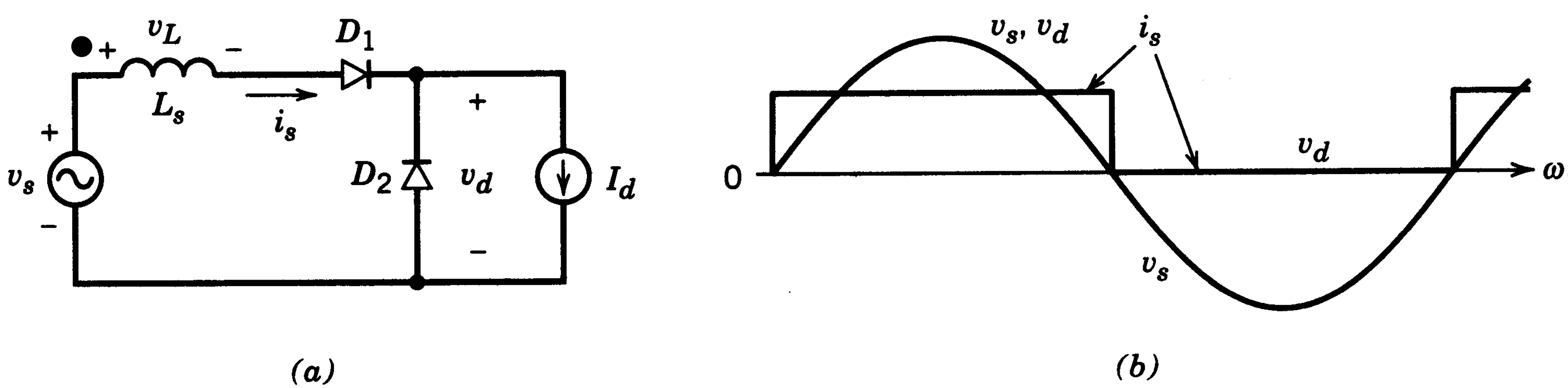


Figure 5-11 Basic circuit to illustrate current commutation. Waveforms assume $L_s = 0$.

Reference: Mohan, Undeland and Robbins, Power Electronics, Converters, Applications and Design, John Wiley, 2003, pp. 87

Current Commutation (cont.)

- Things are not as simple if line inductance is included
  - (All lines have some inductance)
- During "commutation" interval, both diodes are on

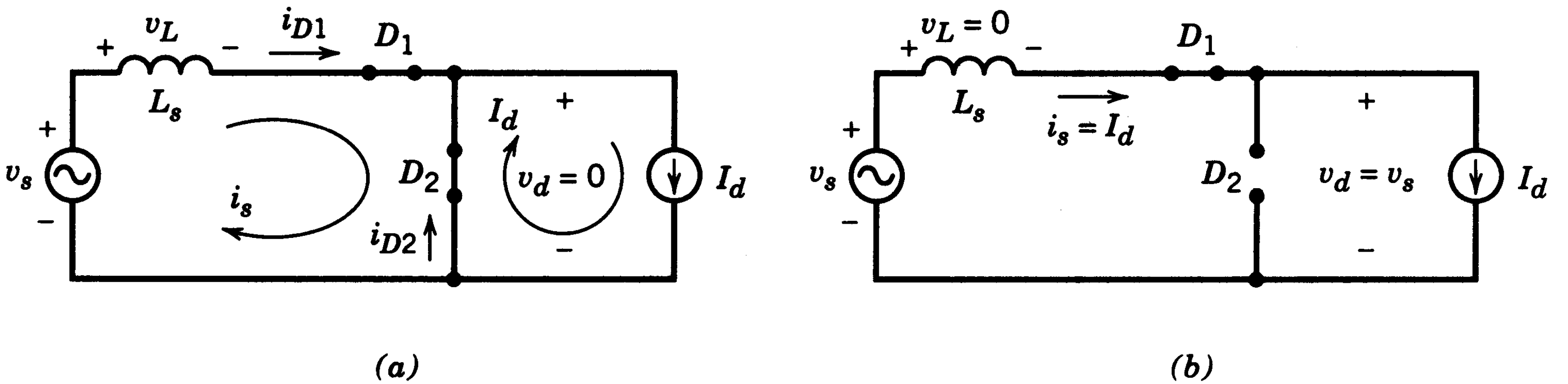


Figure 5-12 (*a*) Circuit during the commutation. (*b*) Circuit after the current commutation is completed.

Reference: Mohan, Undeland and Robbins, Power Electronics, Converters, Applications and Design, John Wiley, 2003, pp. 88

Current Commutation (cont.)

- Shows the volt-seconds needed to commutate current
- 0 < t < u is the “commutation interval” when both diodes are ON

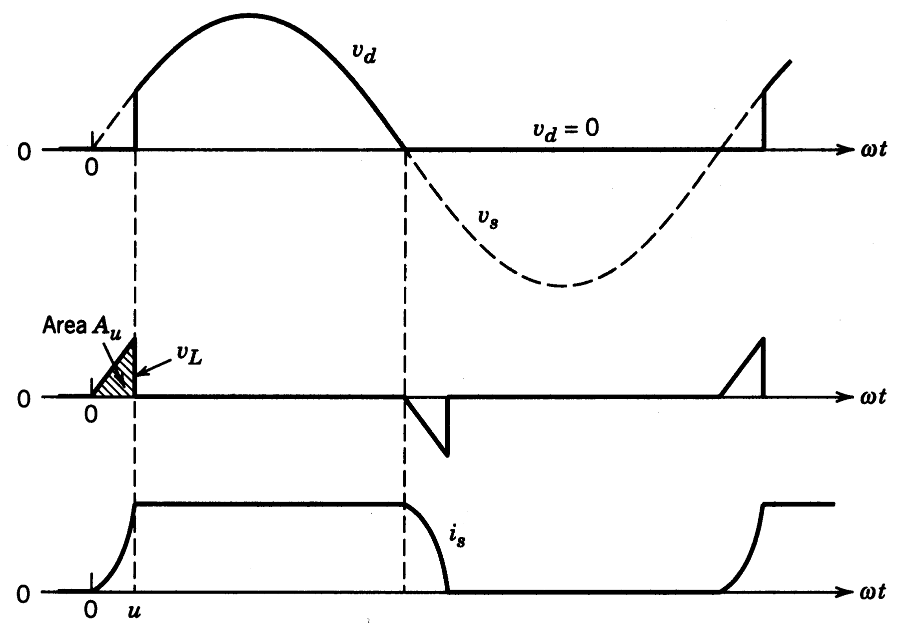


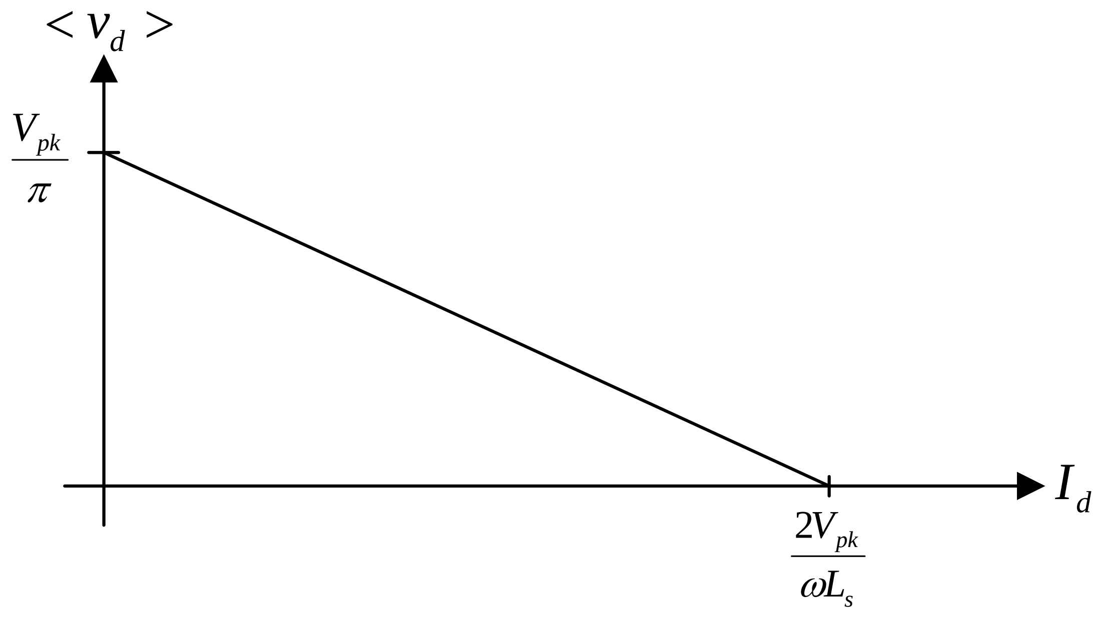
Figure 5-13 Waveforms in the basic circuit of Fig. 5-11. Note that a large value of L_s is used to clearly show the commutation interval.

Reference: Mohan, Undeland and Robbins, *Power Electronics, Converters, Applications and Design*, John Wiley, 2003, pp.88

"Load Regulation"

- Inductance causes output voltage to be lower than that for basic half-wave rectifier
- Average output voltage decreases with output load current

$$< v_d > = \frac{V_{pk}}{2\pi}\int_u^{\pi} \sin x dx = \frac{V_{pk}}{2\pi}(1+\cos u) = \frac{V_{pk}}{\pi}\left(1 - \frac{\omega L_s I_d}{2V_{pk}}\right)$$



Current Commutation in Full-Bridge Rectifier

<u>Commutation process:</u>

ωt<0: D3 and D4 are ON

ωt=0+: v_s becomes positive and D1 and D2 turn ON; v_d = 0 since all 4 diodes are ON

ωt=u : current in D3 and D4 has dropped to zero and they turn OFF; output voltage snaps up to input line voltage

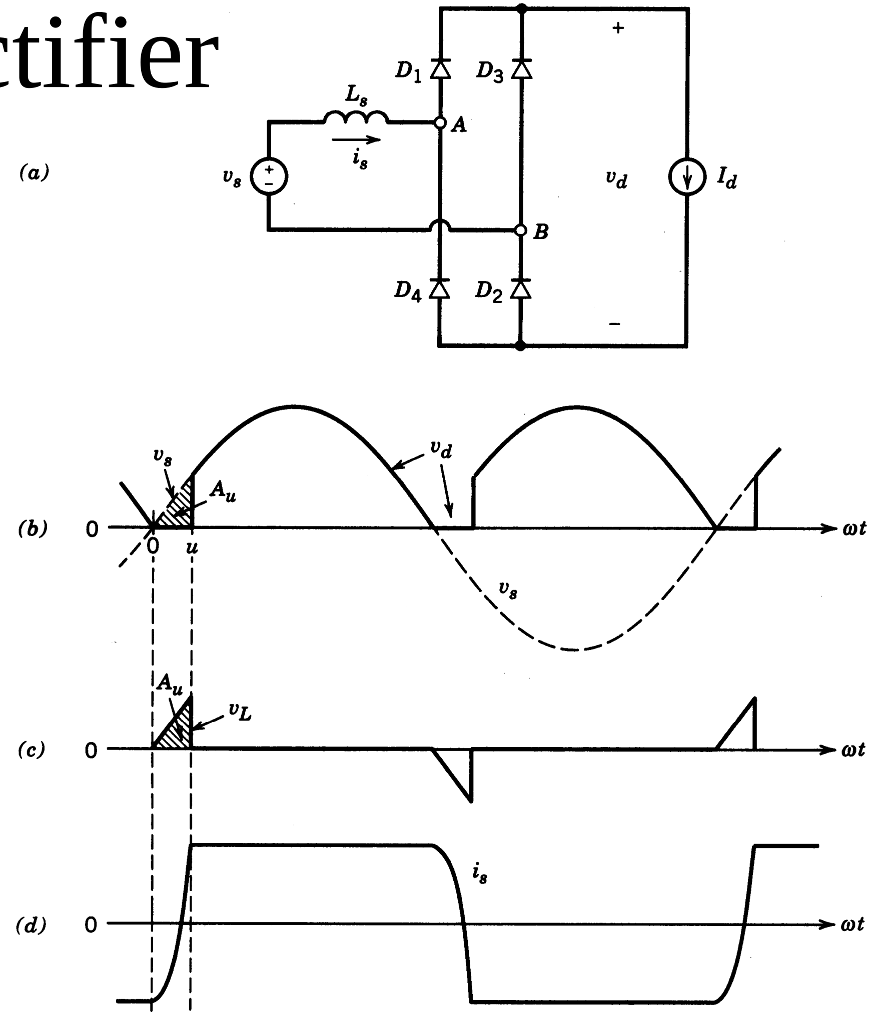


Figure 5-14 (*a*) Single-phase diode rectifier with L_s. (*b*) Waveforms.

Reference: Mohan, Undeland and Robbins, <u>*Power Electronics, Converters, Applications and Design*</u>, John Wiley, 2003, pp. 90

Three-Phase, Full-Bridge Rectifier

- Commonly used in high power applications

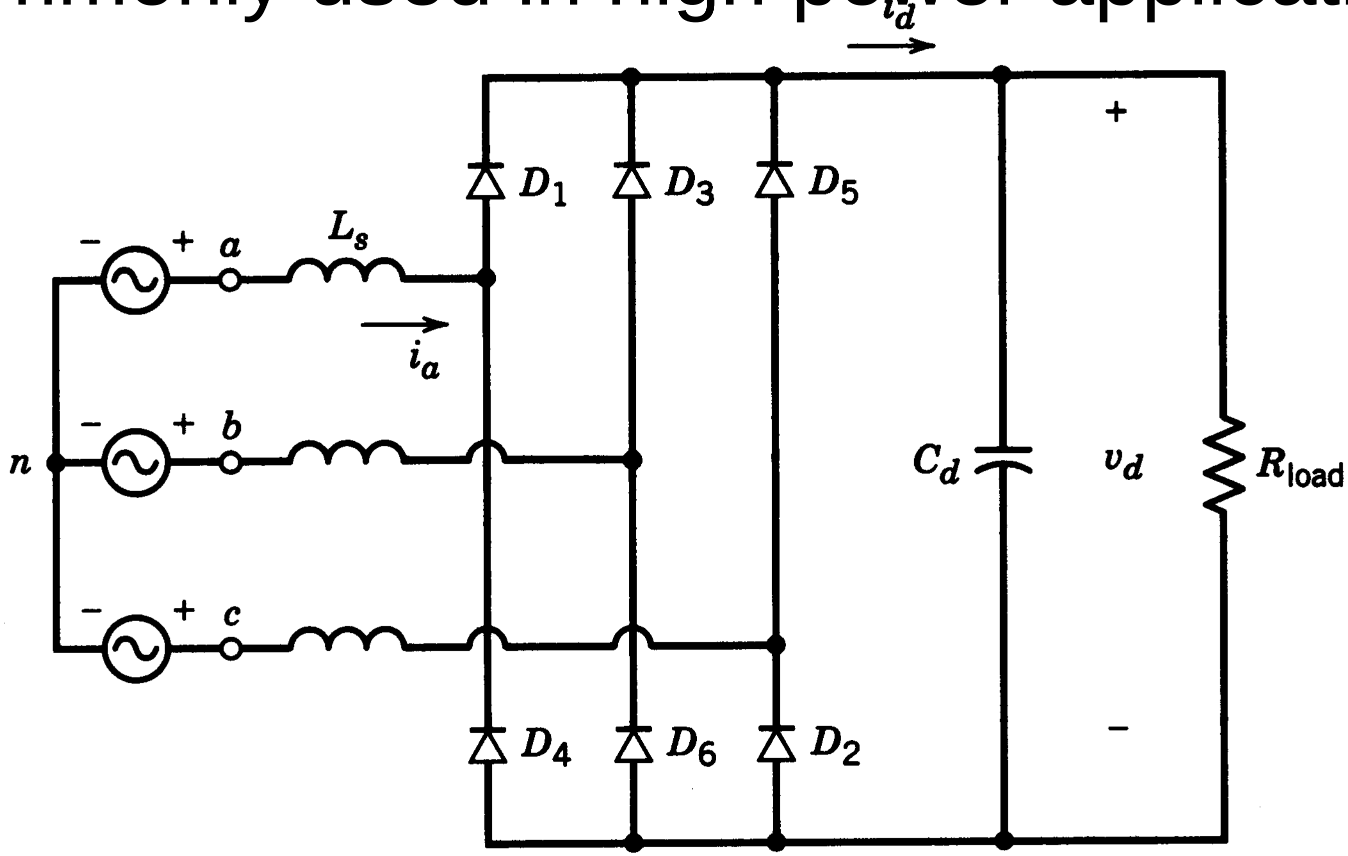
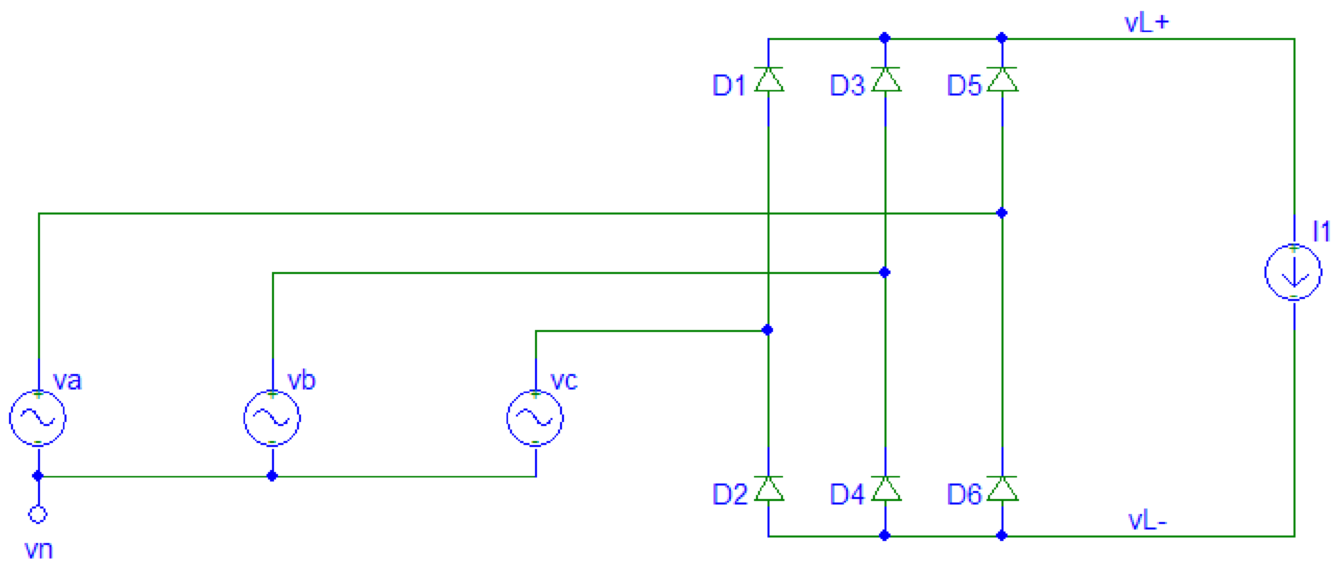


Figure 5-30 Three-phase, full-bridge rectifier.

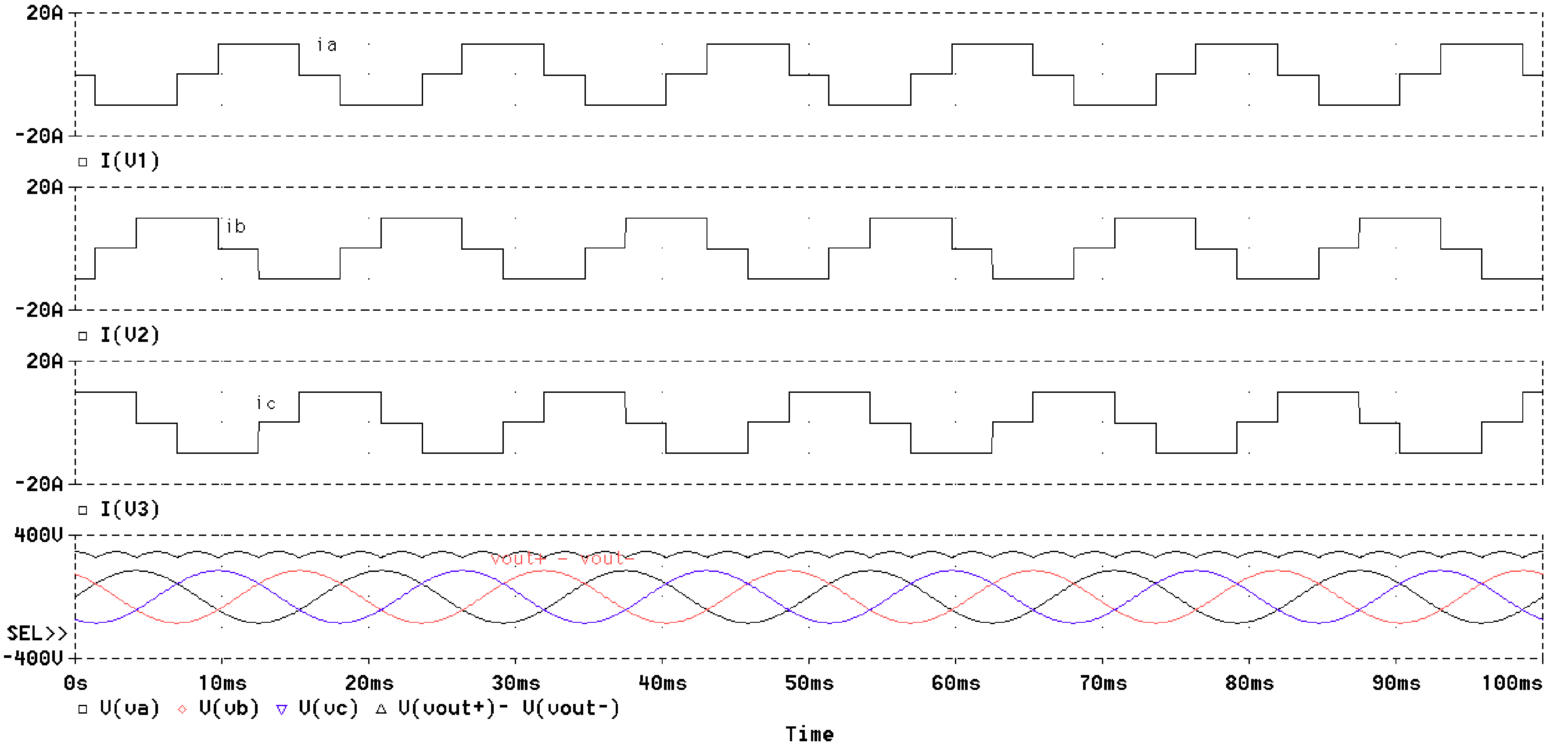
Reference: Mohan, Undeland and Robbins, Power Electronics, Converters, Applications and Design, John Wiley, 2003, pp. 103

Three-Phase Rectifier with Current Source Load

- Simplified with line inductance = 0 and current source load
- Neutral current = 0
- Phase currents do have harmonics



Three-Phase Rectifier with Current Source Load



Three-Phase, Full-Bridge Rectifier

- Shown for output DC current source load

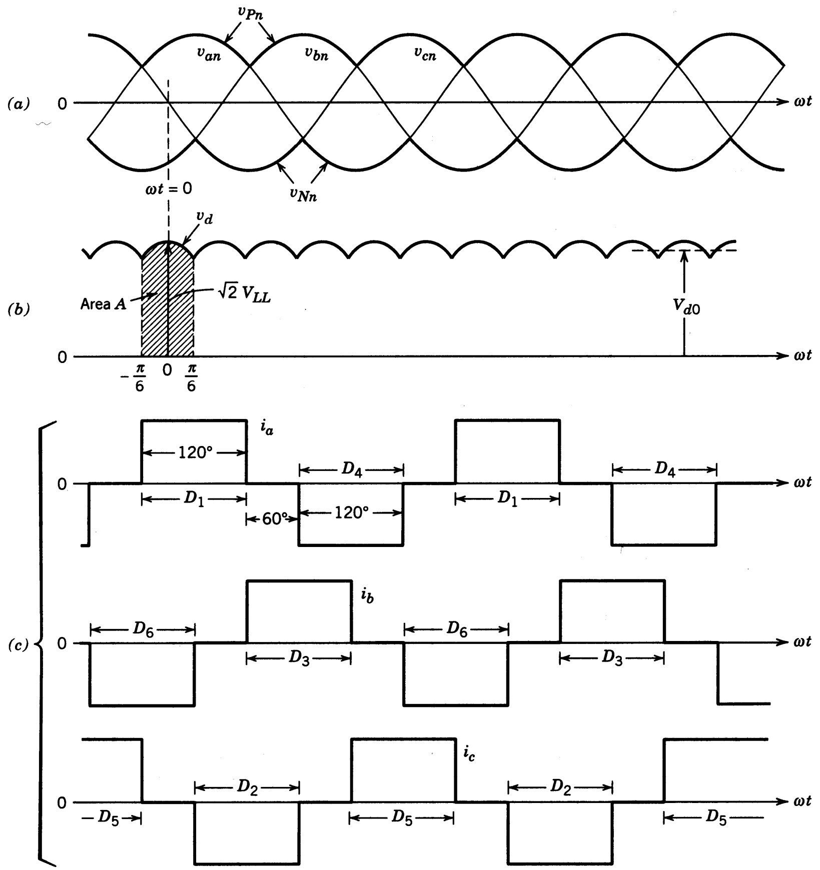


Figure 5-32 Waveforms in the circuit of Fig. 5-31.

Reference: Mohan, Undeland and Robbins, <u>Power Electronics, Converters, Applications and Design</u>, John Wiley, 2003, pp. 104

Three-Phase, Full-Bridge Rectifier: Line Current

- Assuming output current to be purely dc and zero ac-side inductance
- No “triplens”, i.e. 3rd, 9th, etc. harmonics

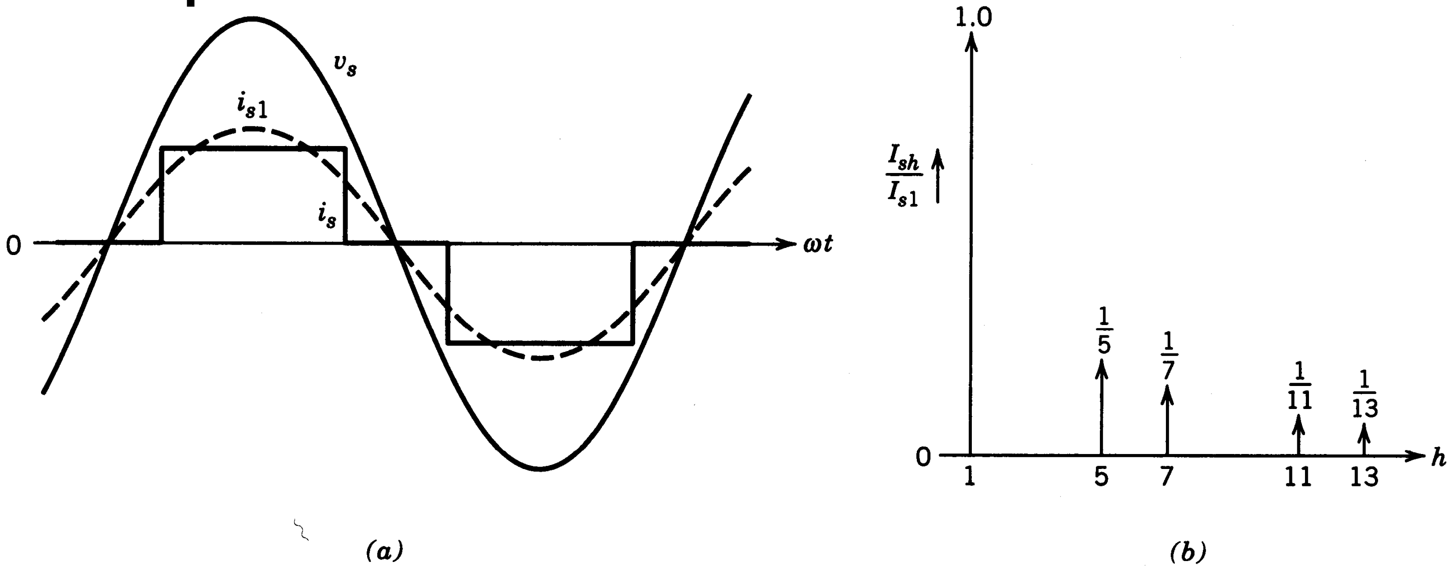
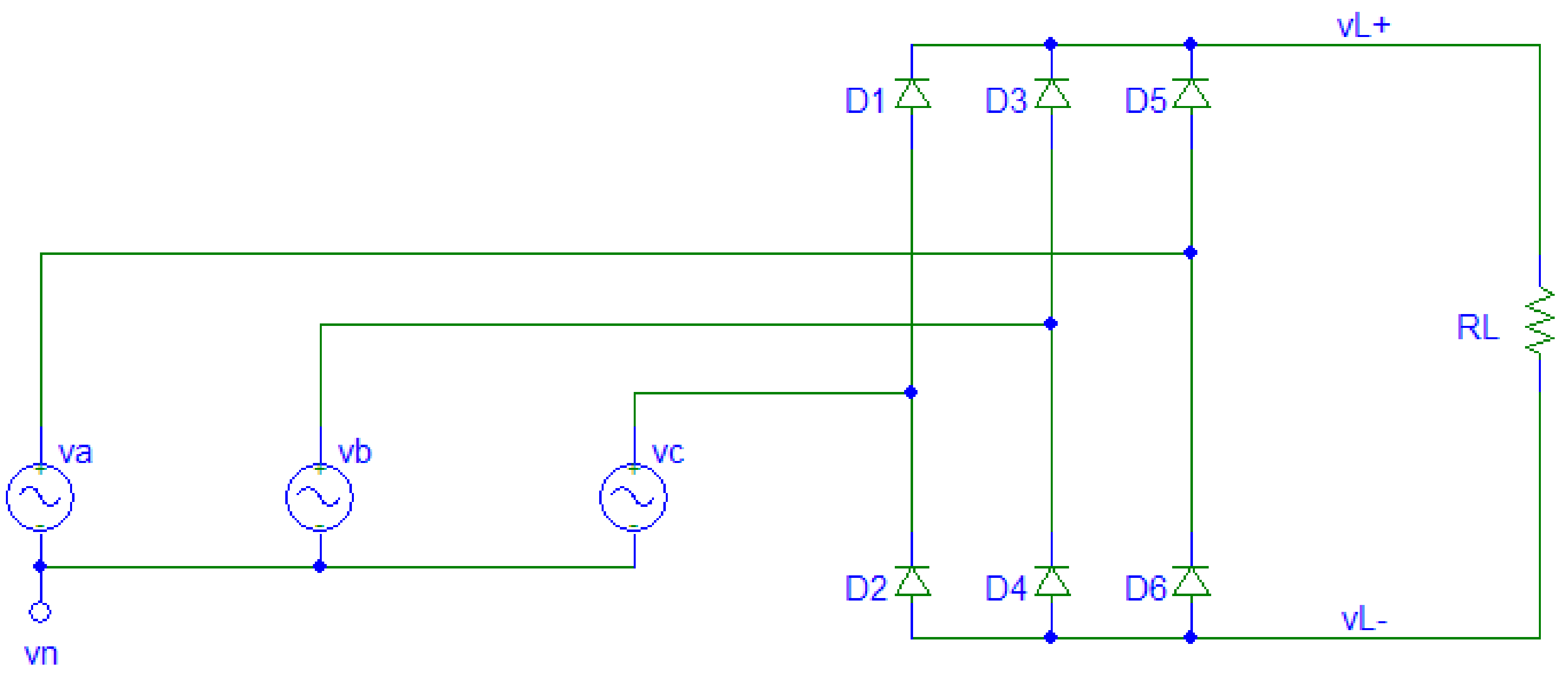


Figure 5-33 Line current in a three-phase rectifier in the idealized case with $L_s = 0$ and a constant dc current.

Reference: Mohan, Undeland and Robbins, Power Electronics, Converters, Applications and Design, John Wiley, 2003, pp. 106

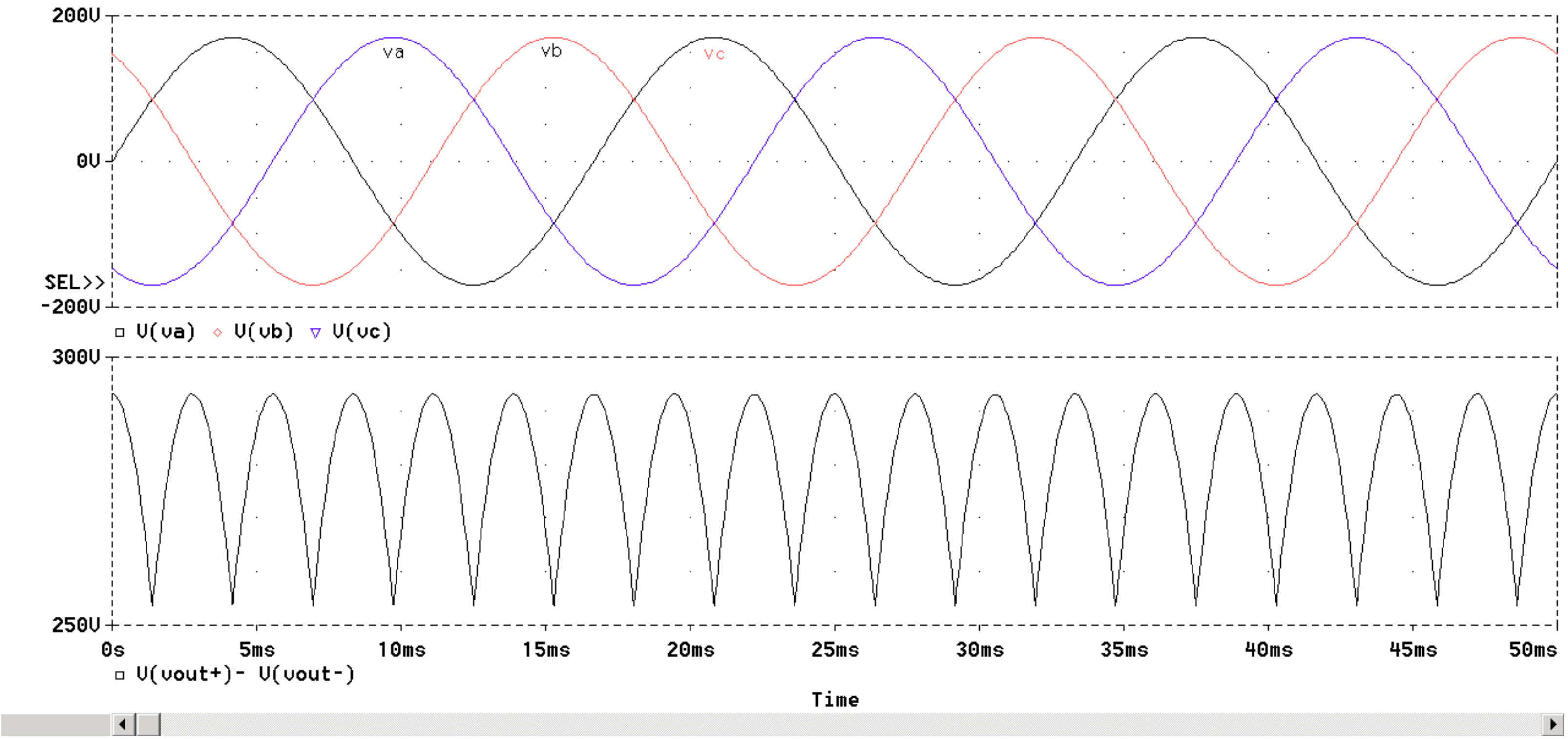
Three-Phase Rectifier with Resistive Load

- Resistive load models high power factor load



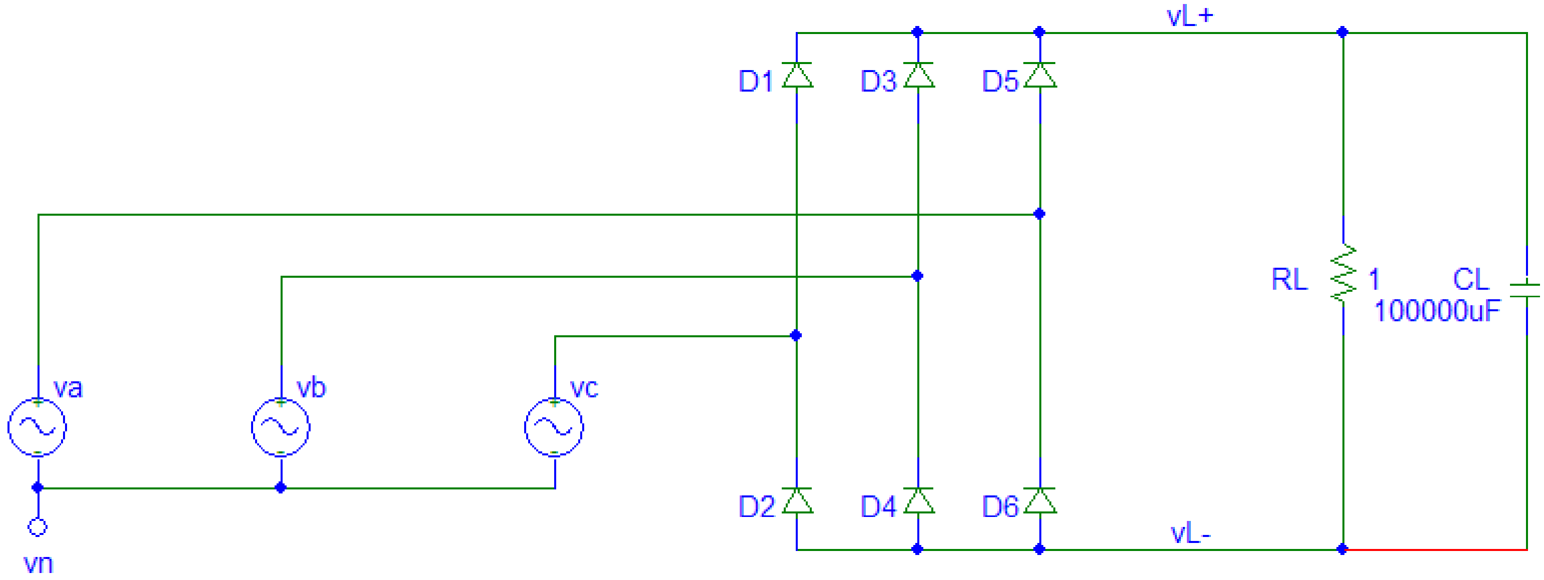
3-Phase Rectifier with Resistive Load --- Output

- Fundamental of ripple frequency = 360 Hz
- Peak value is sqrt(3) x peak of line = 294V

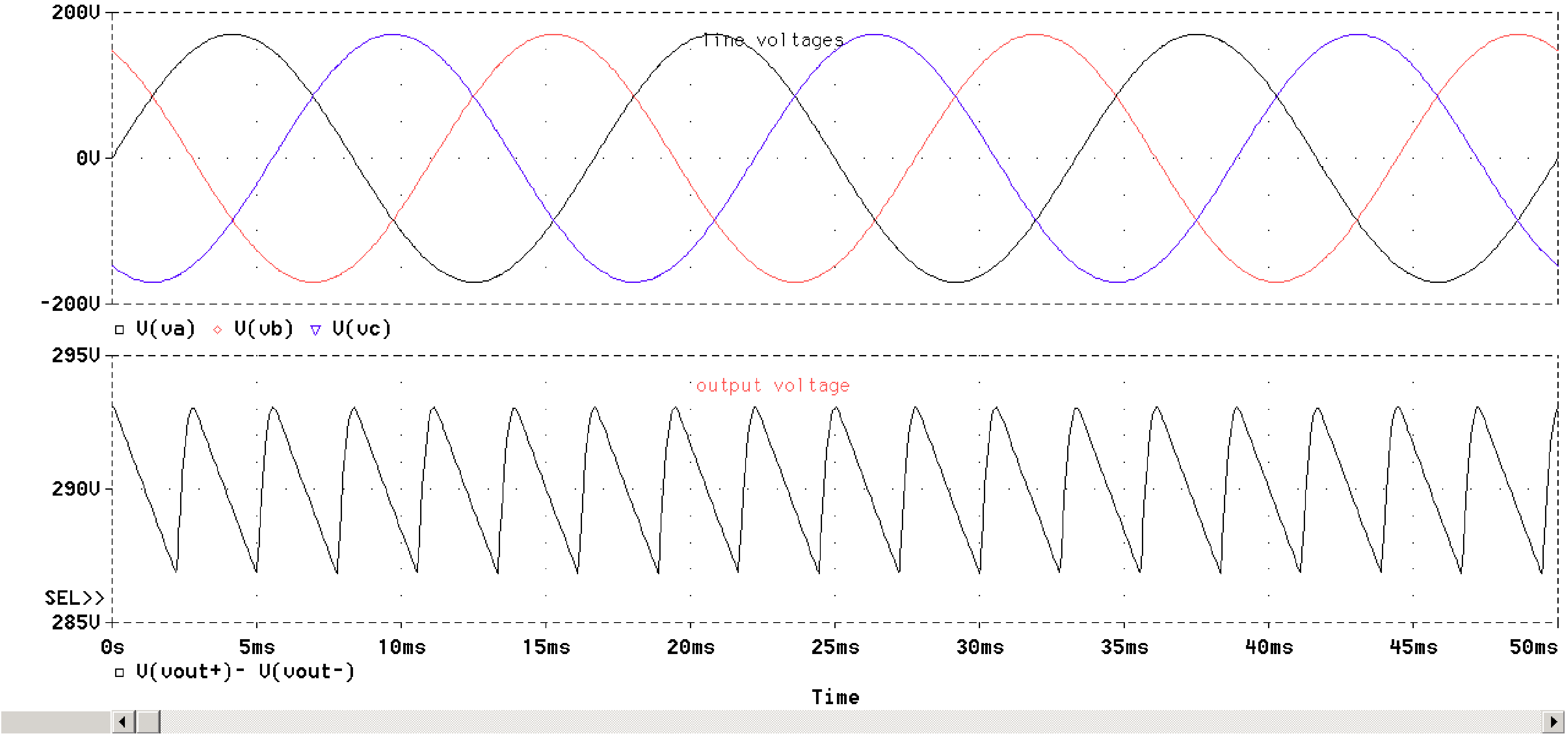


Three-Phase Rectifier with Resistive Load and Capacitor Filter

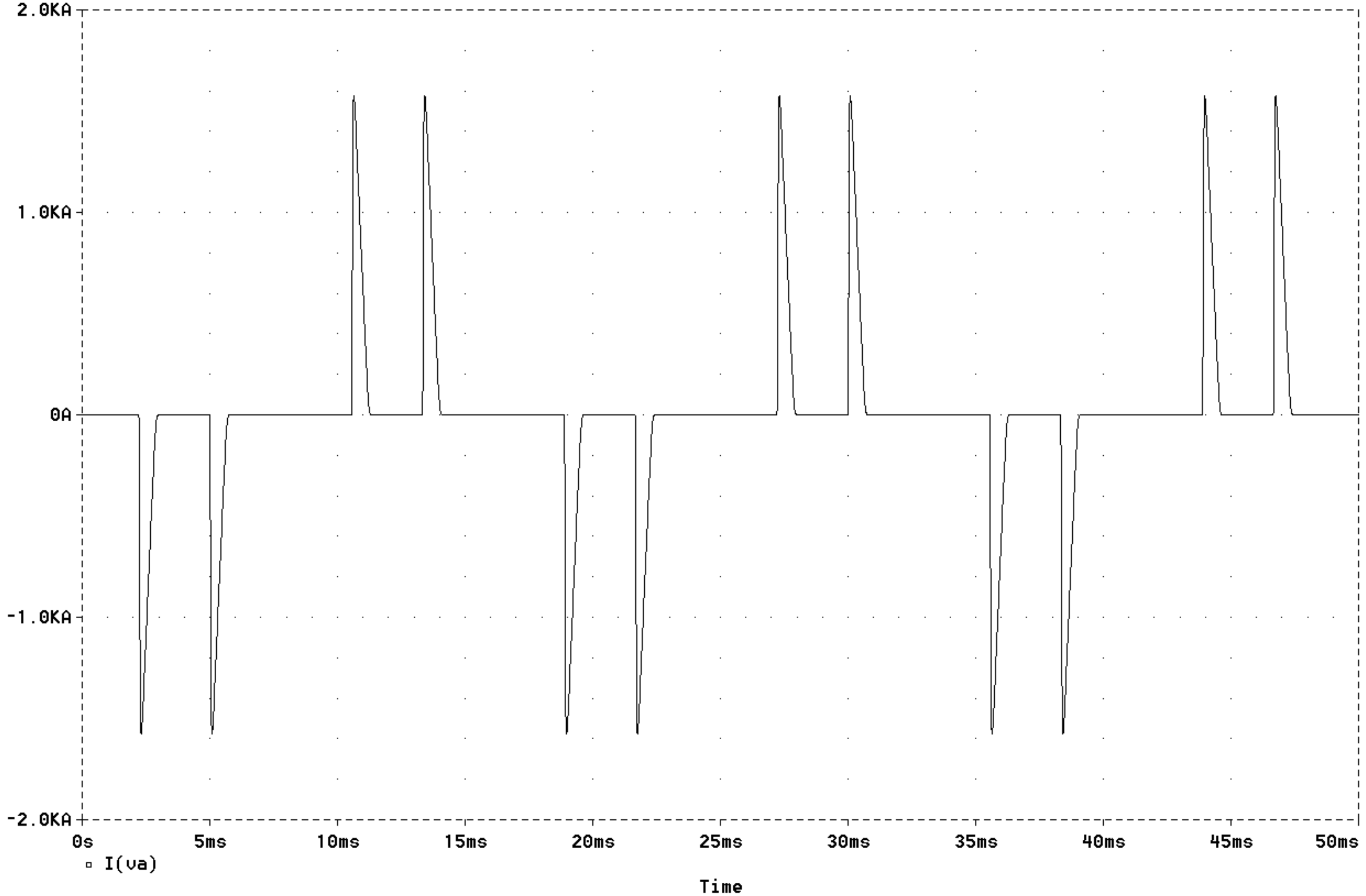
- Note that a smaller capacitor can be used for the 3 phase rectifier compared to single phase rectifier, because (1) Ripple is smaller and (2) Ripple frequency is higher



Three-Phase Rectifier with Resistive Load and Capacitor Filter

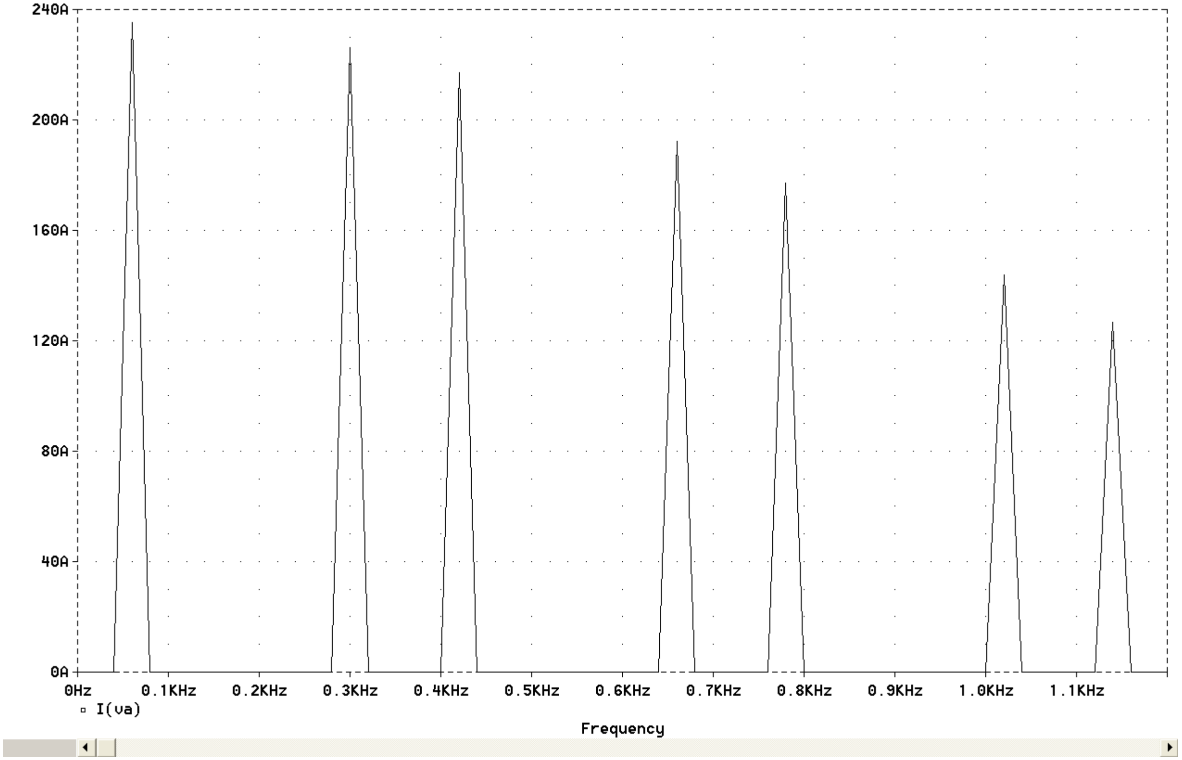


Three-Phase Rectifier with Resistive Load and Capacitor Filter --- Phase Current



3-Phase Rectifier with Resistive Load and Capacitor Filter --- Phase Current Spectrum

- Phase current contains 1st, 5th, 7th, 11th, 15th ... harmonics



Mitigating Strategies

- Harmonic trap
  - Filter designed to pass fundamental and attenuate harmonics
- 12-pulse rectifier: harmonics are 11th, 13th, 23rd, 25th, ...
  - 12-pulse eliminates 5th, 7th, 17th, 19th, ... harmonics
  - Requires Y-Y and Delta-Y transformers, and 12 diodes

Three-Phase, Full-Bridge Rectifier: Redrawn

- Two groups with three diodes each

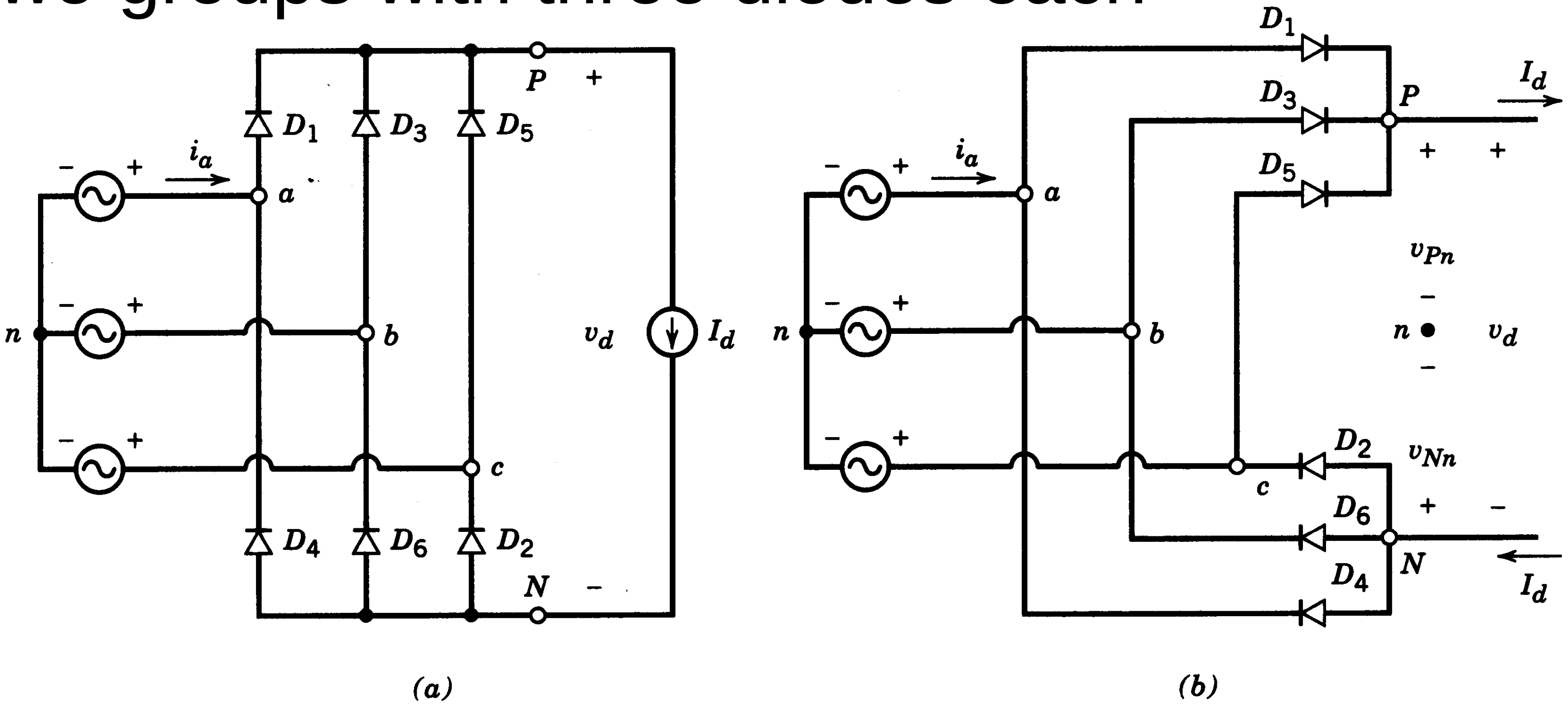


Figure 5-31 Three-phase rectifier with a constant dc current.

Reference: Mohan, Undeland and Robbins, Power Electronics, Converters, Applications and Design, John Wiley, 2003, pp. 103

Three-Phase, Full-Bridge Rectifier

- Including the ac-side inductance means that we have another commutation process

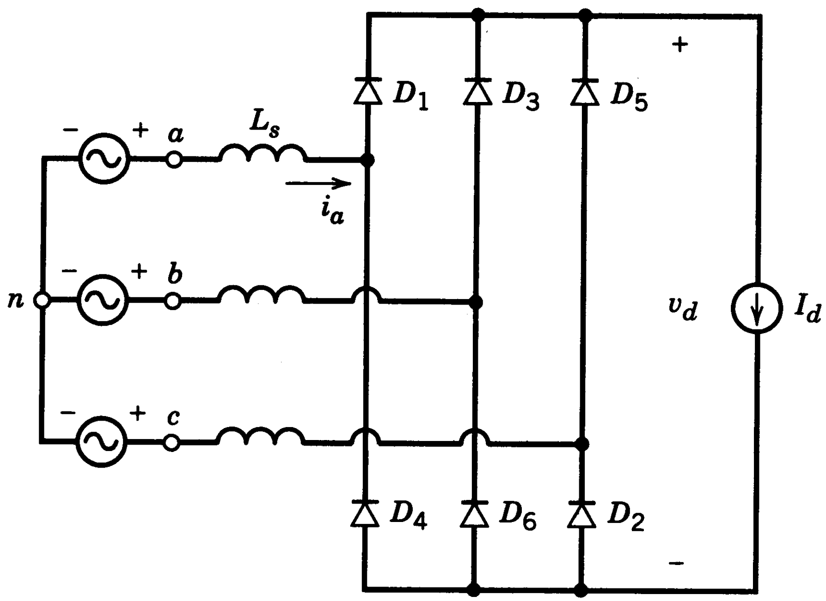


Figure 5-34 Three-phase rectifier with a finite L_s and a constant dc current.

Reference: Mohan, Undeland and Robbins, Power Electronics, Converters, Applications and Design, John Wiley, 2003, pp. 106

3-Phase Rectifier: Current Commutation

- Output current is assumed to be purely dc

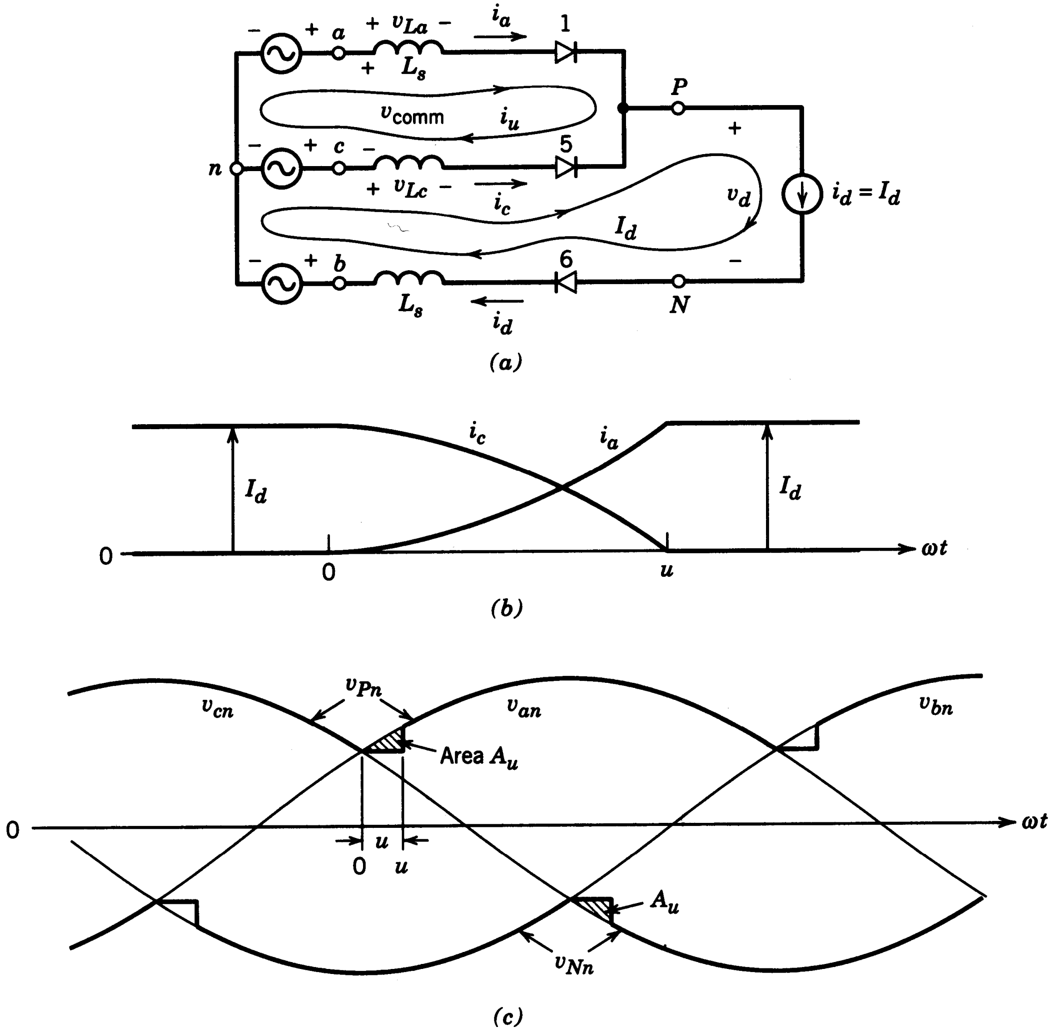


Figure 5-35 Current commutation process.

Reference: Mohan, Undeland and Robbins, _Power Electronics, Converters, Applications and Design_, John Wiley, 2003, pp. 107

Ramifications of Harmonics

- Triplens can cause buildup of neutral current; neutral current can exceed phase current
- Noise in power lines
- Buzzing of power panels

A Three-Phase, Four-Wire System

- With single-phase nonlinear loads, there can be a neutral current

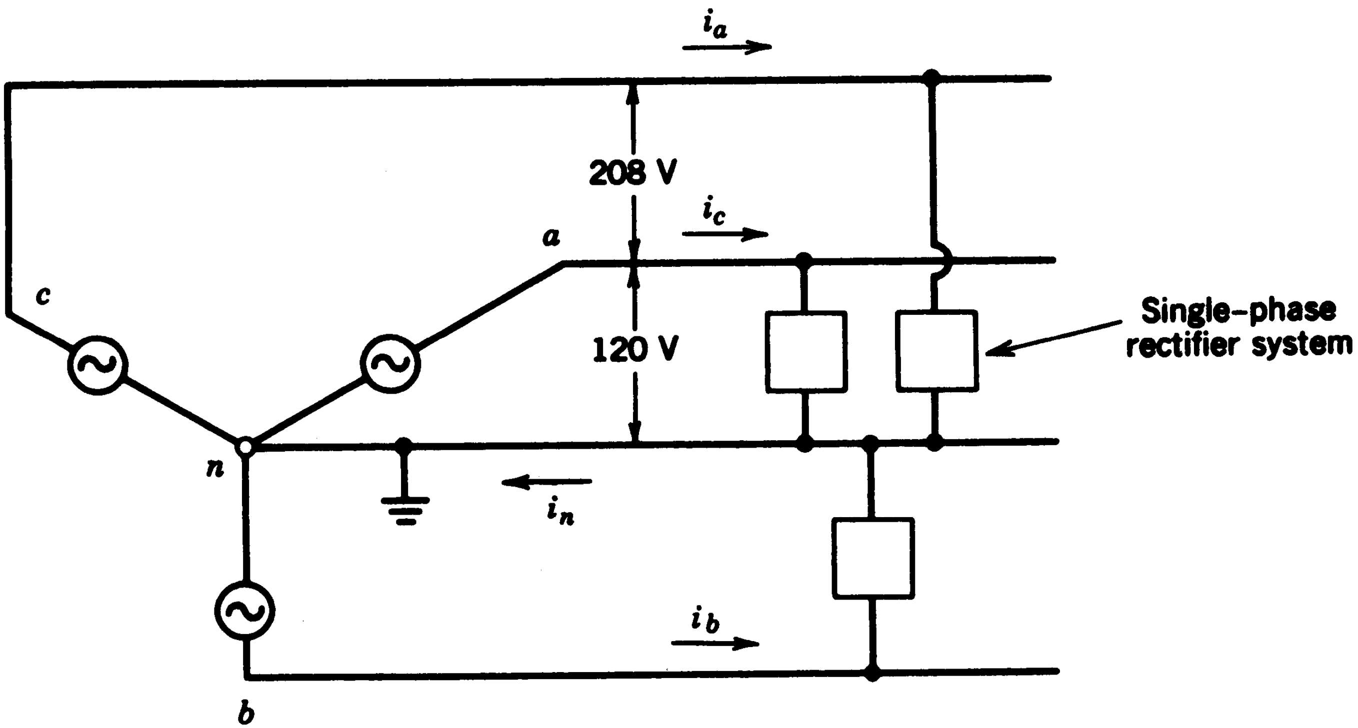


Figure 5-28 Three-phase, four-wire system.

Reference: Mohan, Undeland and Robbins, *Power Electronics, Converters, Applications and Design*, John Wiley, 2003, pp. 101

Current in a 3-Phase, Four-Wire System

- The neutral current can be very high if driving nonlinear loads line to neutral
- If line currents are highly discontinuous, the neutral current can be as large as 1.73xline current 3rd harmonic
- Note 3rd harmonic here

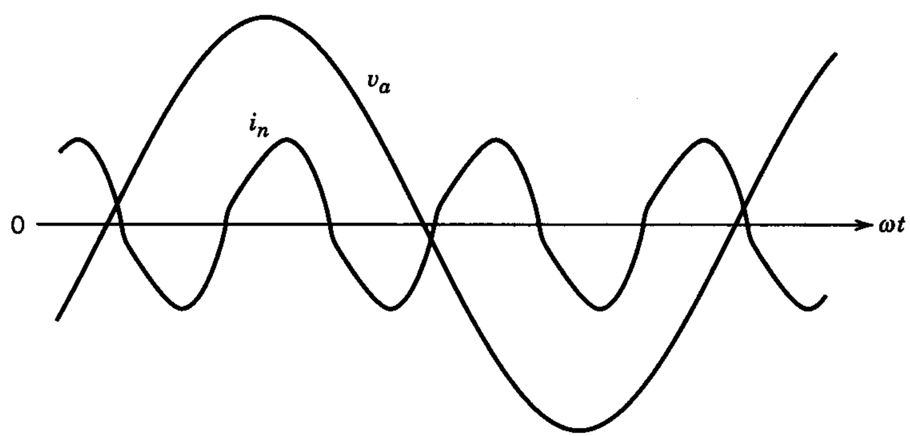
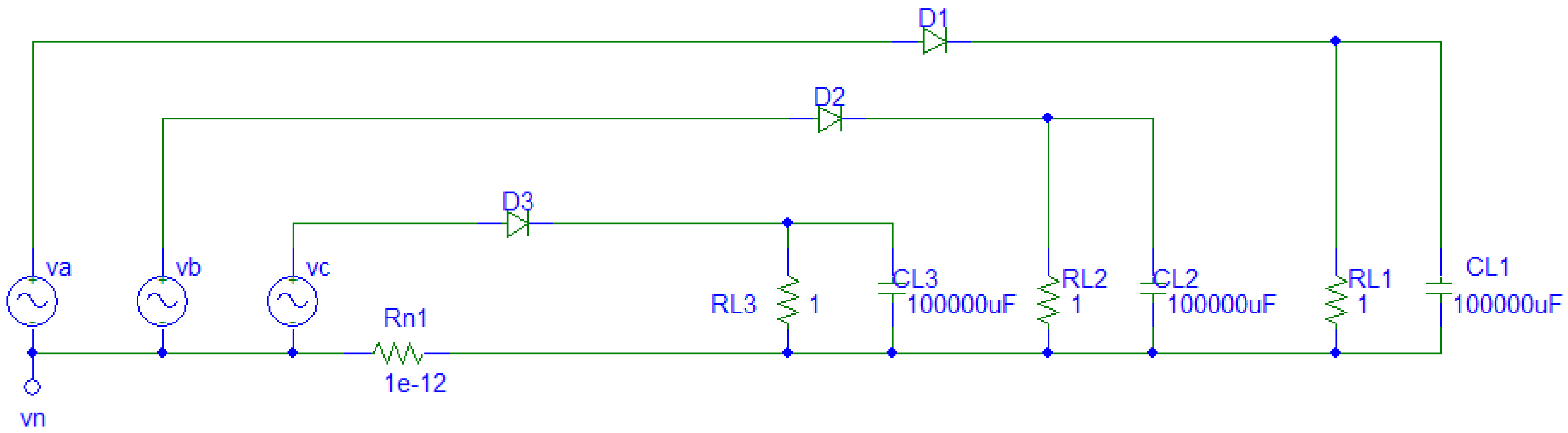


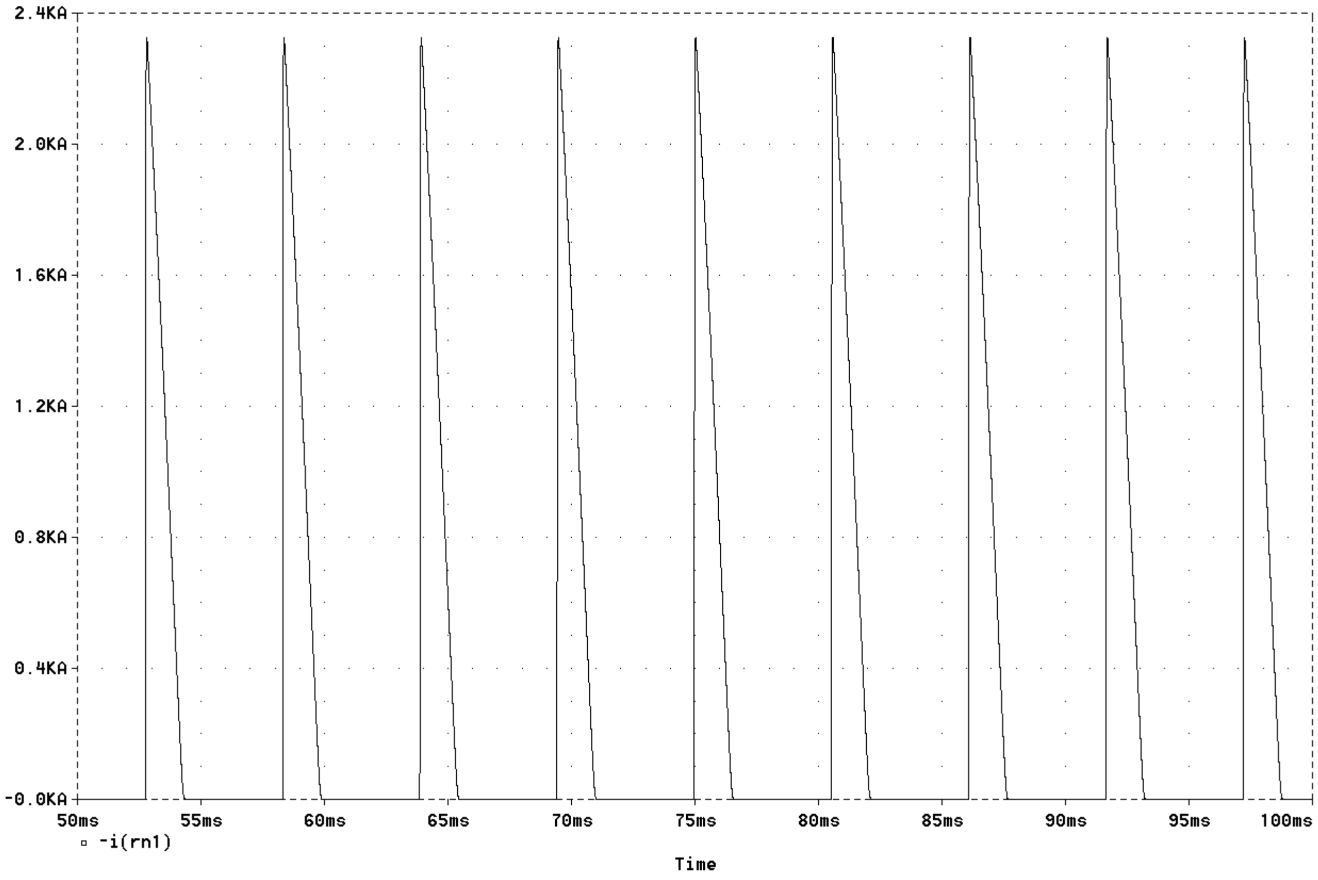
Figure 5-29 Neutral-wire current i_n.

Reference: Mohan, Undeland and Robbins, <u>Power Electronics, Converters, Applications and Design</u>, John Wiley, 2003, pp. 102

Simulation of Simple Case



Simulation of Simple Case --- Neutral Current



Simulation of Simple Case --- Spectrum of Neutral Current