TSTE19 Power Electronics

Lecture 2
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Lecture 2, outline

- Diode device characteristics
  - Semiconductor theory
  - Data sheet info
- Rectifiers
  - Single phase
- Characteristics
  - Total Harmonic Distortion (THD)
  - Crest Factor
  - Power Factor
- Exercises: 5-1, 5-2, 5-3, 5-4, 5-7, 5-14

Lecture 2

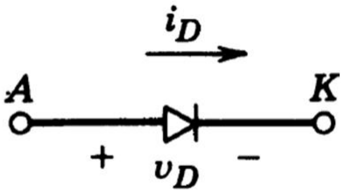
Diode device characteristics

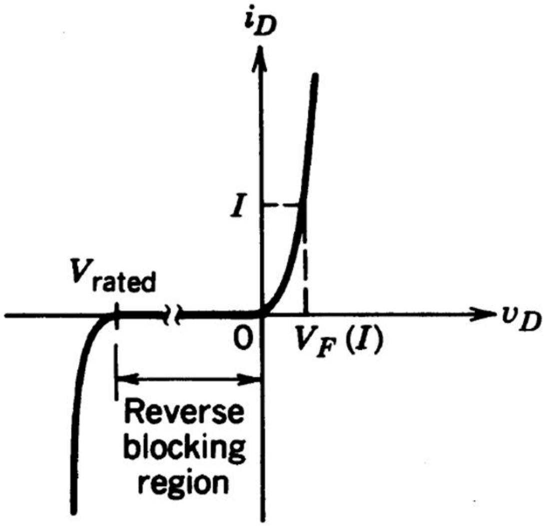
Semiconductor theory

Data sheet info

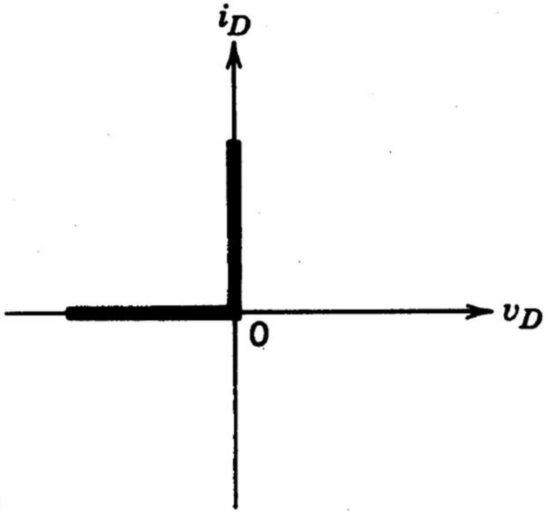
Diodes

- Characteristic



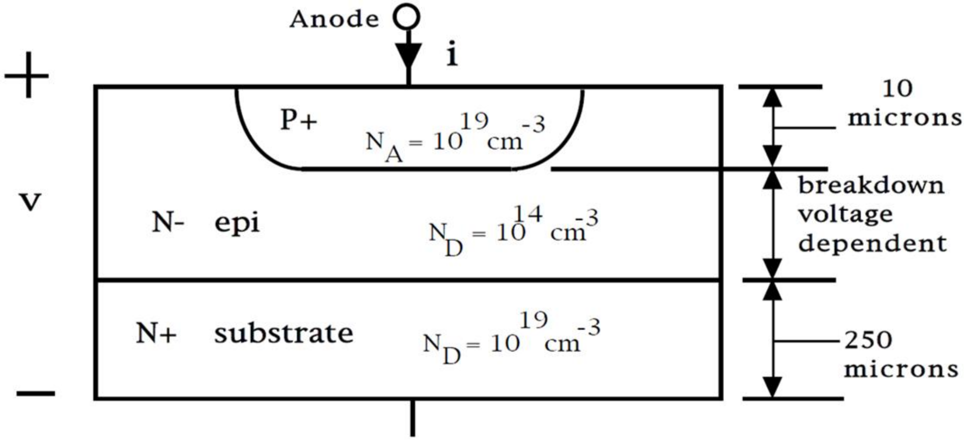


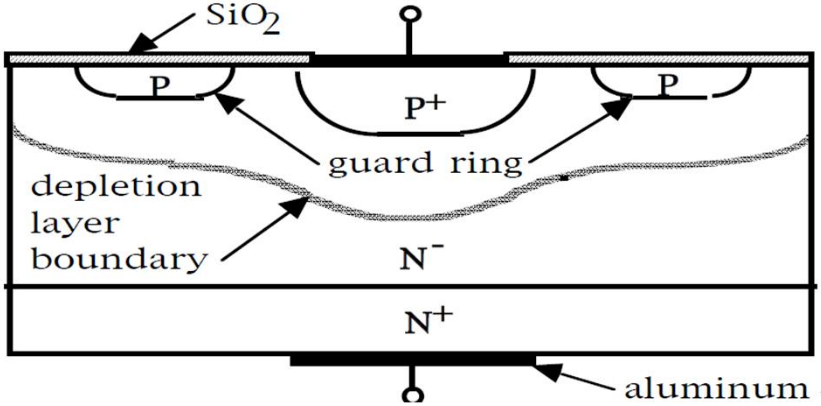
- Idealized characteristic
  - Neglect forward voltage drop
  - Neglect breakdown voltage
  - Turns off only if current drops to 0

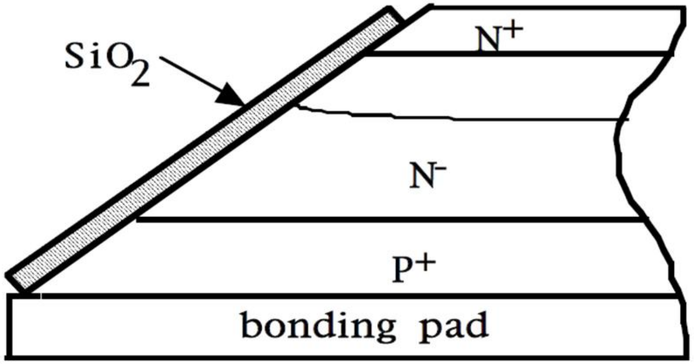


Diodes, physical implementation

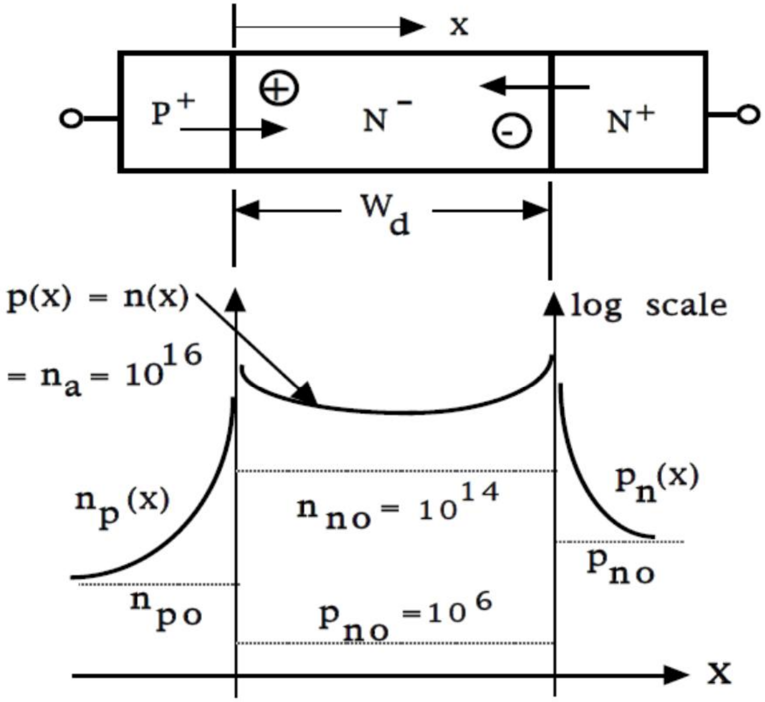
- P-N junction
- Cross-section area for kA diodes are several square cm
- Additional structures to increase breakdown voltage







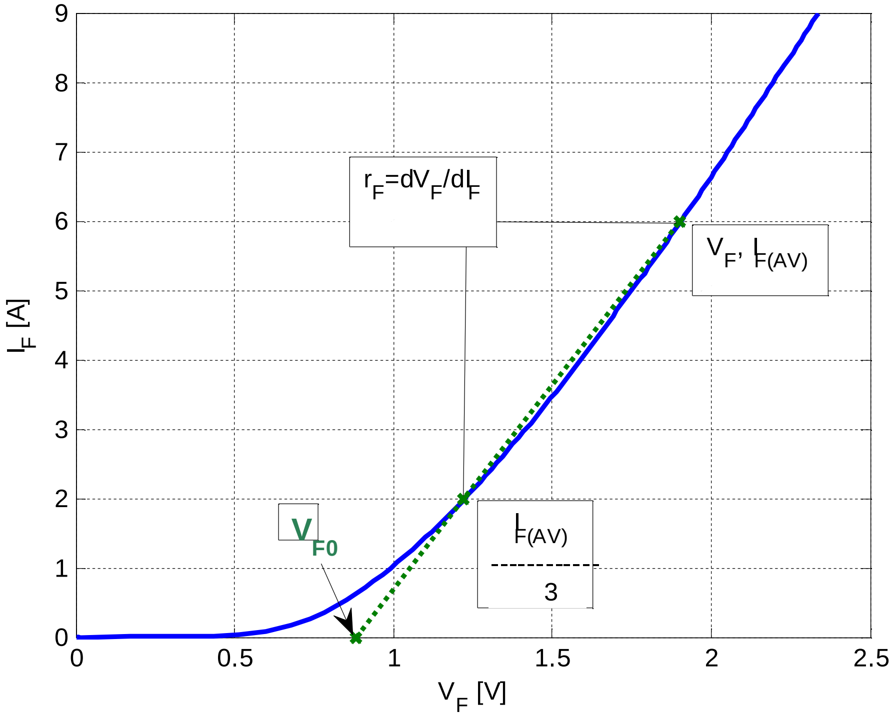
On-state: Carrier injection



- Forward bias injects holes into drift region from P⁺ layer. Electrons attracted into drift region from N⁺ layer. So-called double injection.
- If $W_d \leq$ high level diffusion length L_a, carrier distributions quite flat with $p(x) \approx n(x) \approx n_a$.
- For n_a >> drift region doping N_d, the resistance of the drift region will be quite small. So-called conductivity modulation.
- On-state losses greatly reduced below those estimated on basis of drift region low-level (N_d) ohmic conductivity.

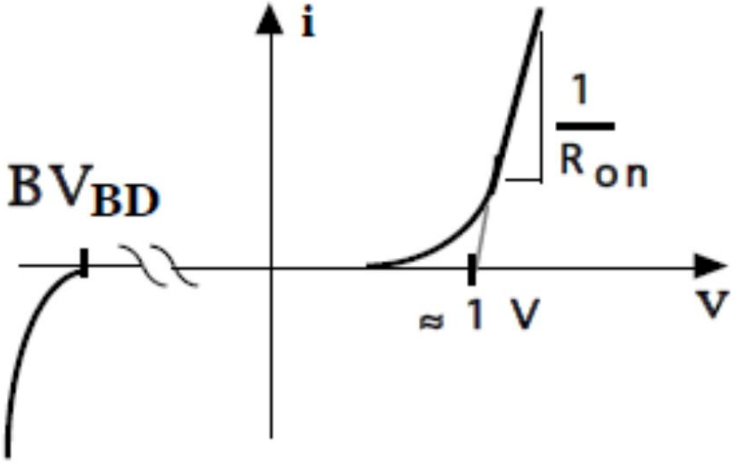
On-state diode data

- Data sheet
- $I_{F(AV)}$ = Average forward current
- V_F = Voltage at $I_{F(AV)}$
- 1^{st} order model
- On-state chracateristics simplified to a straight line through $I_{F(AV)}$ and $I_{F(AV)}/3$
- $\Rightarrow V_{F0}$ and r_F
- I_{FRM} = repetitive peak forward current
- I_{FSM} = non-repetitive (surge) forward current



Off-state diode data

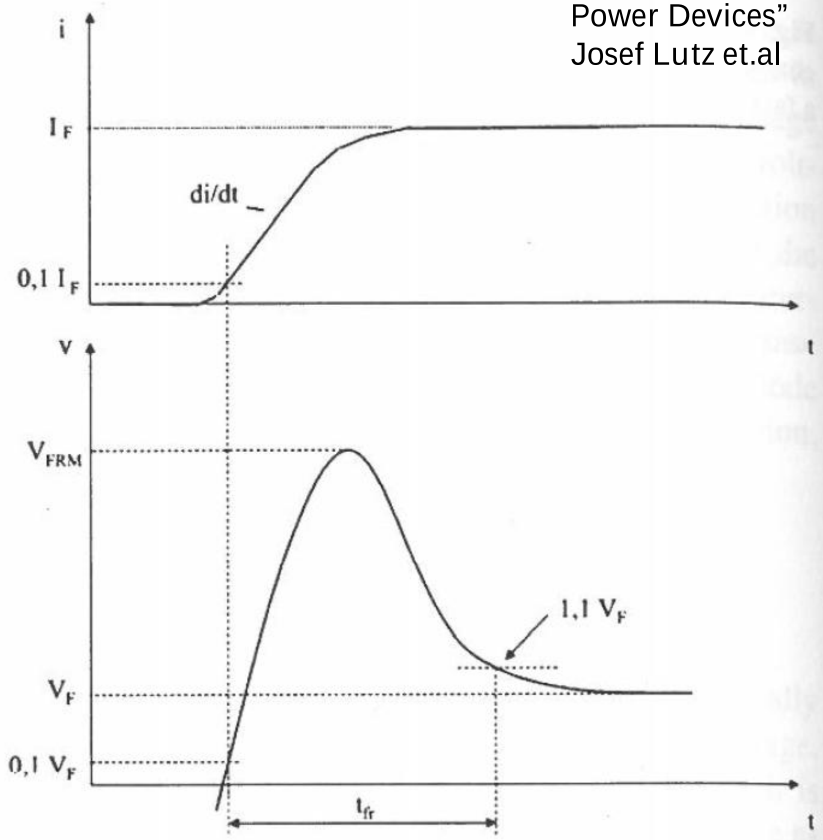
- V_{RRM} = repetitive peak reverse voltage
- I_R = reverse leakage current
- I_{RRM} = repetitive peak reverse current



Diode behaviour during turn-on

”Semiconductor Power Devices” Josef Lutz et.al

Fig. 5.13 Characteristic parameters of the turn-on behavior of power diodes



- Over-voltage during diode turn-on
- = Forward recovery
- Initial low carrier concentration gives high voltage
- V_{FRM} = Forward recovery voltage

Diode behaviour during turn-off

- High carrier concentration in the diode at turn-off
- Carriers need to be removed for the diode to block voltage
- Removal of carriers = negative current
- Carriers removed by negative voltage
- = Reverse recovery
- Q_{rr} = Stored charge extracted
- I_{rr} = Peak reverse recovery current
- t_{rr} = Time until 25% of I_{rr}.

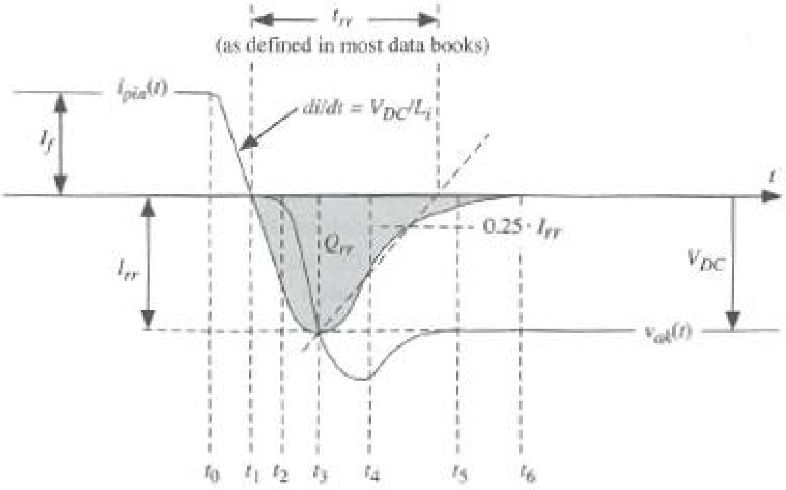


Fig. 3.8 Switching behavior of a pin-diode in the test circuit of Figure 3.7.

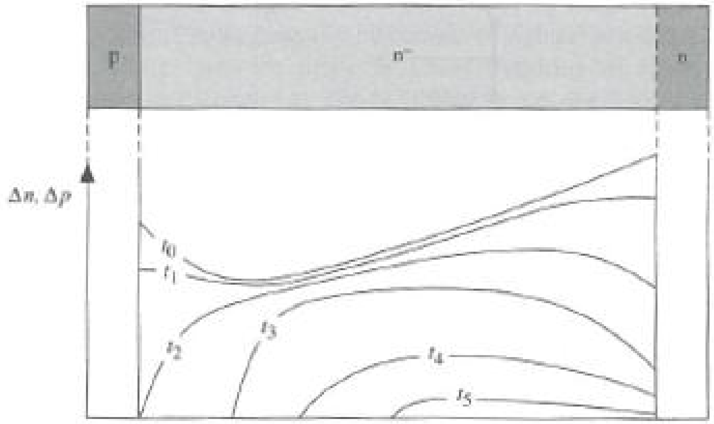
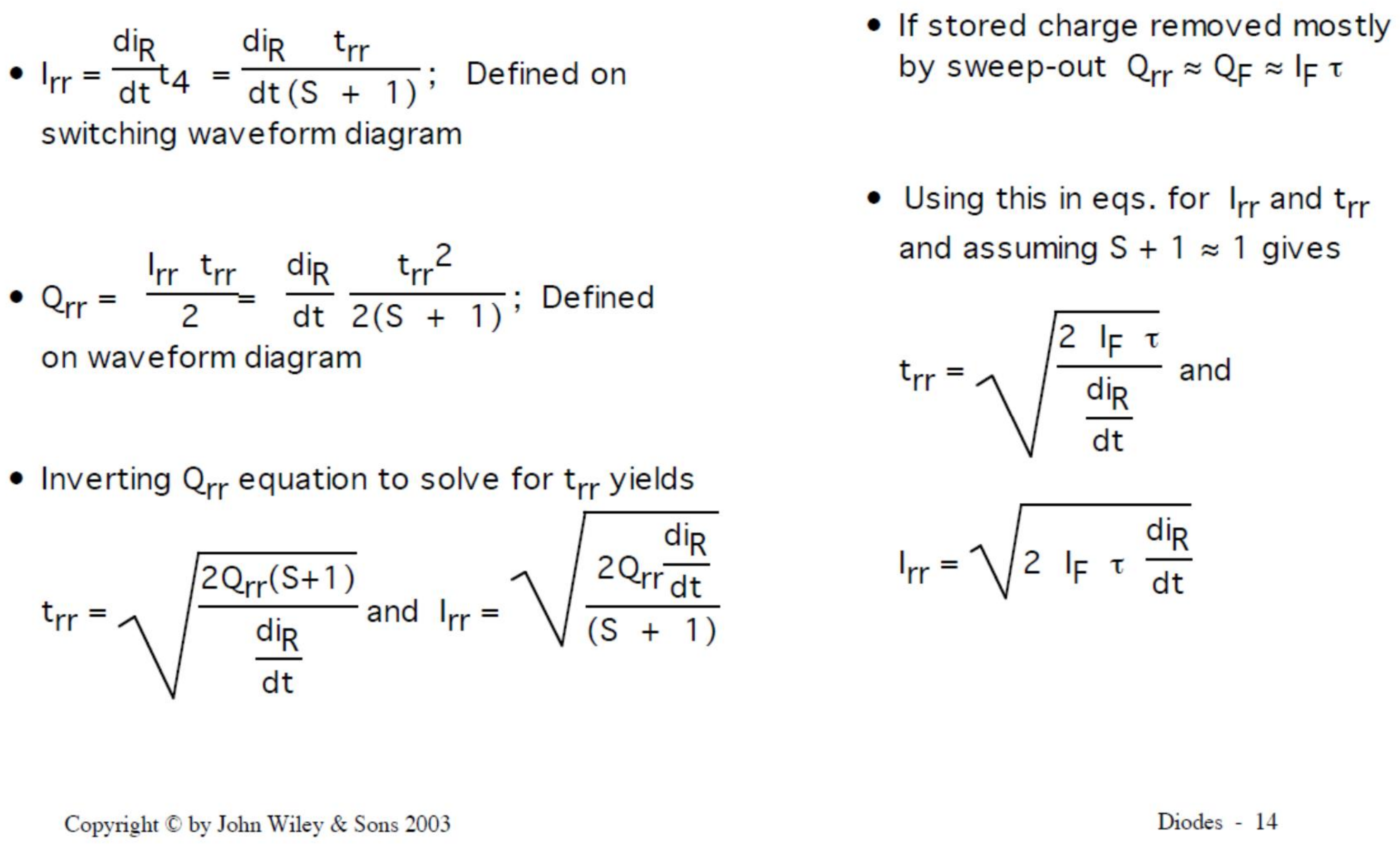


Fig. 3.9 Curves for the excess carrier concentration in the pin-diode, at the instants marked in Figure 3.8.

Turn-off, reverse recovery factors



- $I_{rr} = \frac{di_R}{dt} t_4 = \frac{di_R}{dt} \frac{t_{rr}}{(S+1)}$; Defined on switching waveform diagram

- $Q_{rr} = \frac{I_{rr} \; t_{rr}}{2} = \frac{di_R}{dt} \frac{t_{rr}^2}{2(S+1)}$; Defined on waveform diagram

- Inverting Q_{rr} equation to solve for t_{rr} yields

$$t_{rr} = \sqrt{\frac{2Q_{rr}(S+1)}{\frac{di_R}{dt}}} \text{ and } I_{rr} = \sqrt{\frac{2Q_{rr}\frac{di_R}{dt}}{(S+1)}}$$

- If stored charge removed mostly by sweep-out $Q_{rr} \approx Q_F \approx I_F \, \tau$

- Using this in eqs. for I_{rr} and t_{rr} and assuming $S + 1 \approx 1$ gives

$$t_{rr} = \sqrt{\frac{2 \, I_F \, \tau}{\frac{di_R}{dt}}} \text{ and}$$

$$I_{rr} = \sqrt{2 \, I_F \, \tau \frac{di_R}{dt}}$$


BYW29E-200

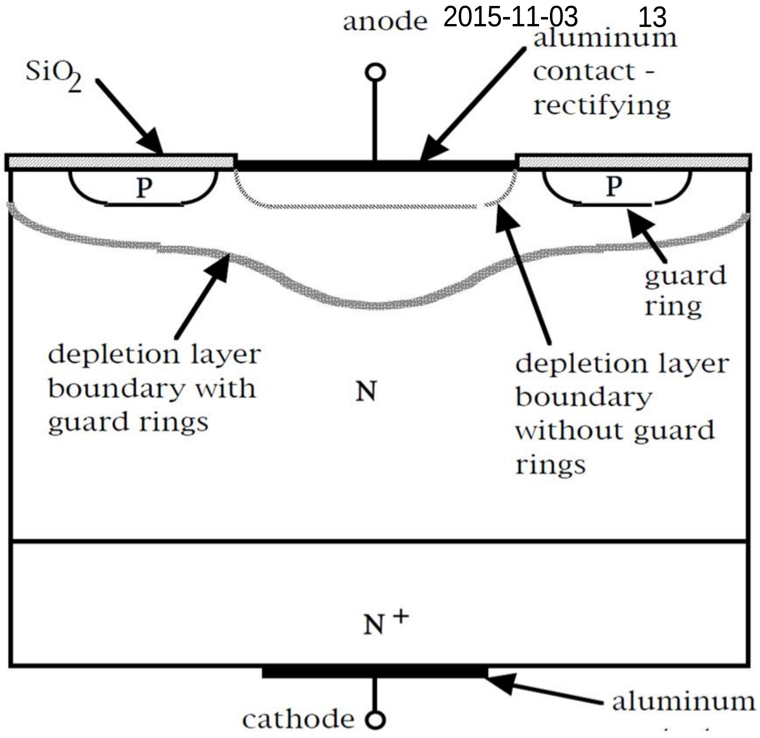
Ultrafast power diode

Rev. 5 — 20 March 2012 Product data sheet

- Electrical data
- Thermal data
- Mechanical data
- BYW29E-200_eng_tds.pdf

•Diode types

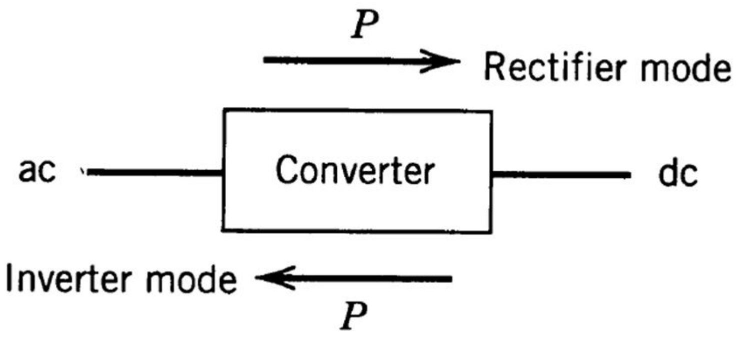
- Schottky
    - Forward voltage ~ 0.3 V
    - Blocking voltage range 50 - 100V
- Fast-recovery
    - trr small (< few microseconds for diodes for 100:s Volt blocking voltage and 100:s Ampere current rating)
- Line-frequency
    - Small forward voltage, little larger irr, large blocking voltage and current rating



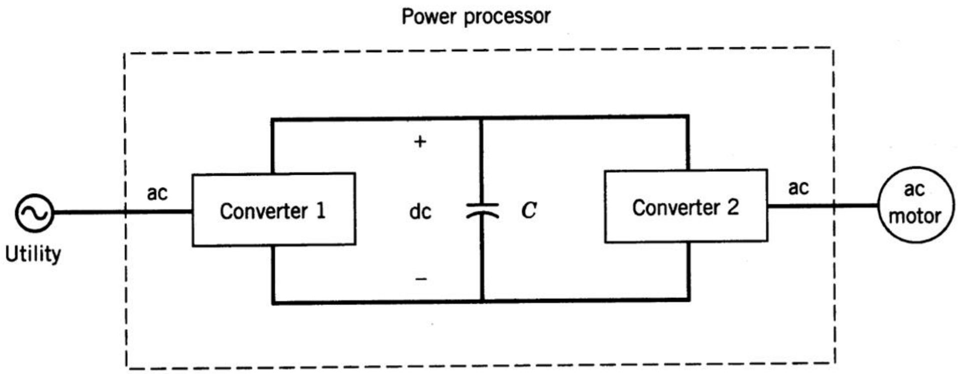
Lecture 2

- Rectifiers
  - Single phase
- Characteristics
  - Total Harmonic Distortion (THD), Crest Factor, Power Factor

Rectifiers vs inverters

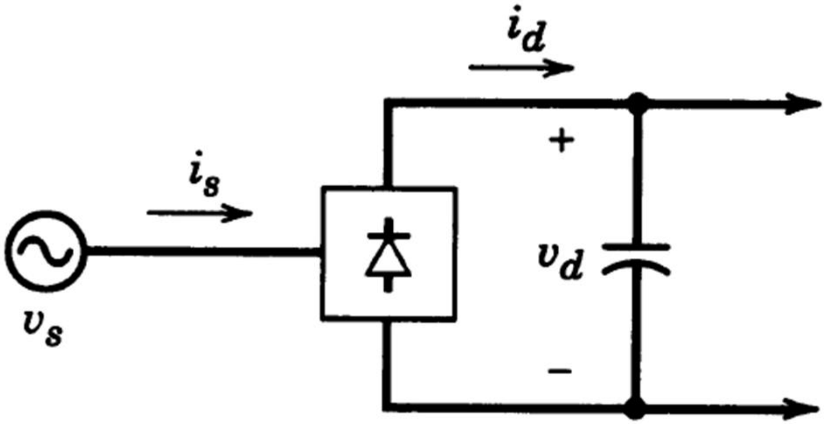


- Principle
  - AC -> DC: rectifier {likriktare}
  - DC -> AC: inverter {växelriktare}
- Output may be controlled or uncontrolled
  - Uncontrolled e.g. AC-DC diode rectifier
- AC frequency may be fixed or varying
  - Motor control: varying
  - Line frequency 50 Hz (Europe)



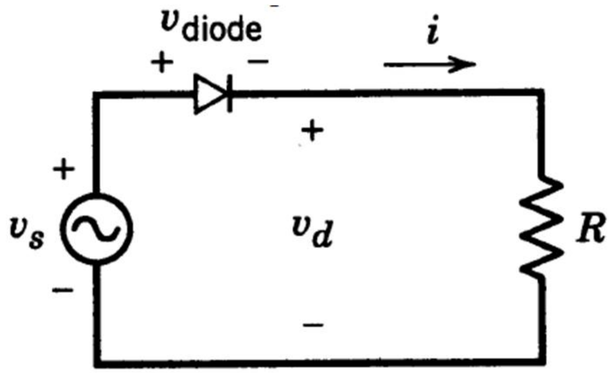
Line frequency diode rectifier

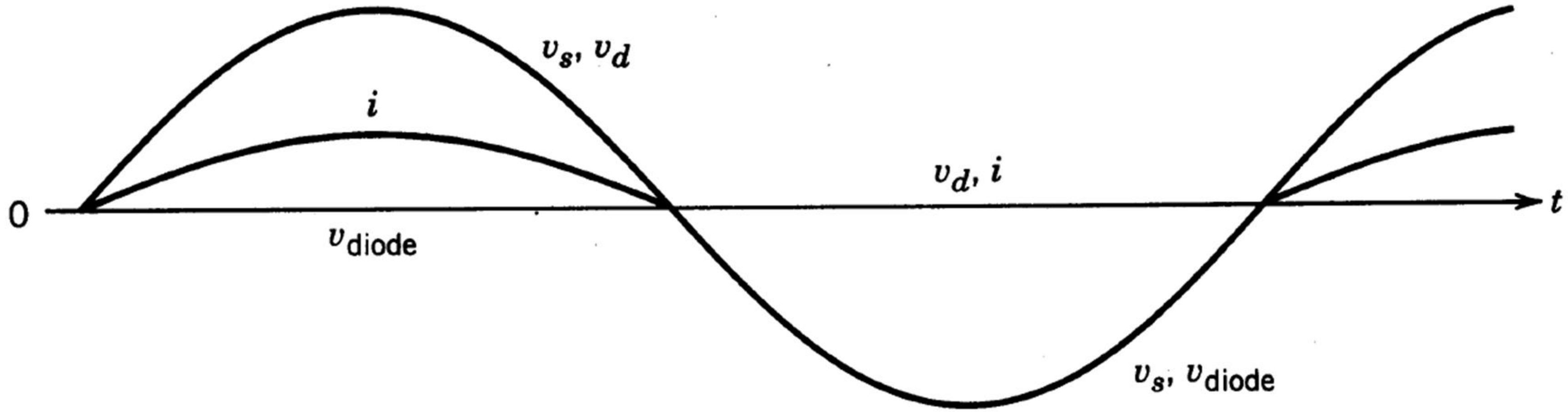
- Line frequency AC -> uncontrolled DC
- Limit DC-side ripple
  - C added at output
- Assume ideal diode



Inductive load

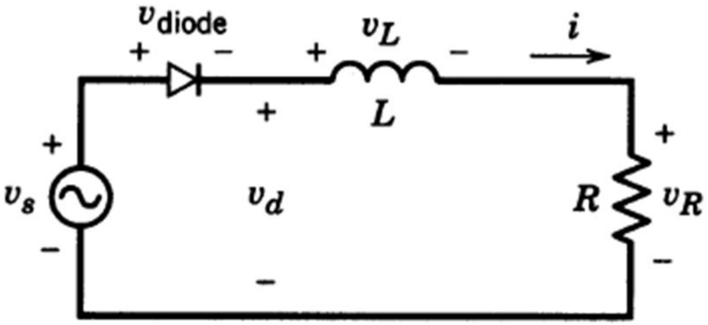
- Big ripple on i and v_d
- Half-wave rectifier

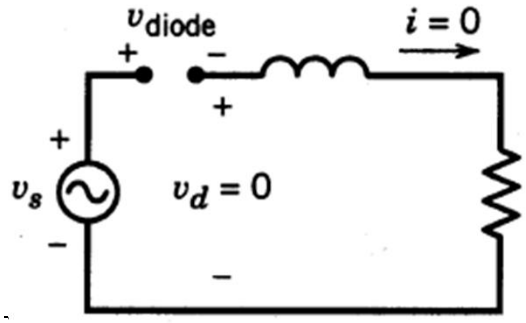


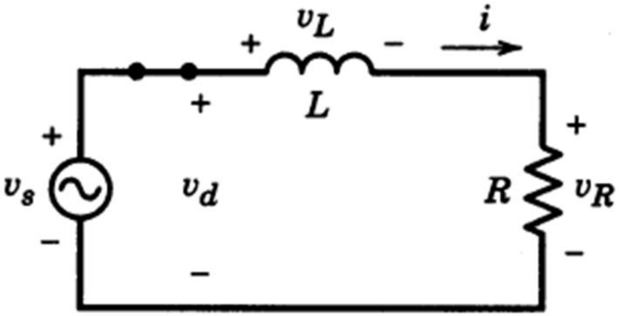


Inductive load

- Two modes
  - Current = 0
  - Current <> 0
- Two schematics, diode on and off
- Diode off => $v_d = 0$

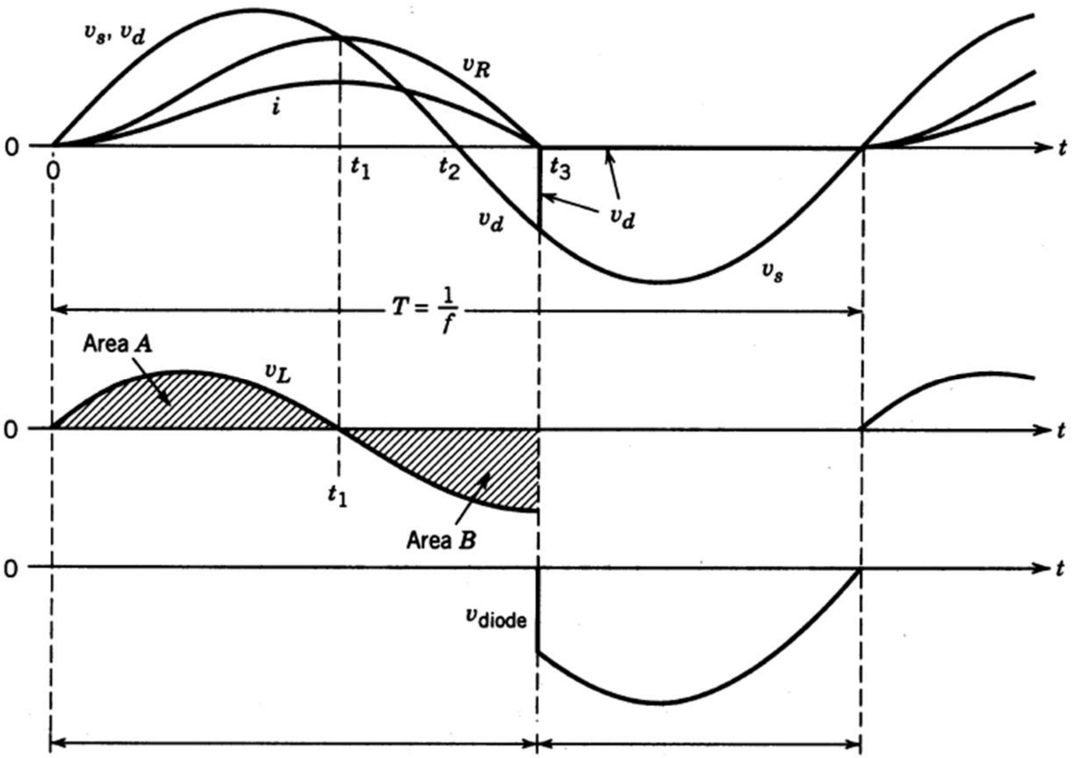




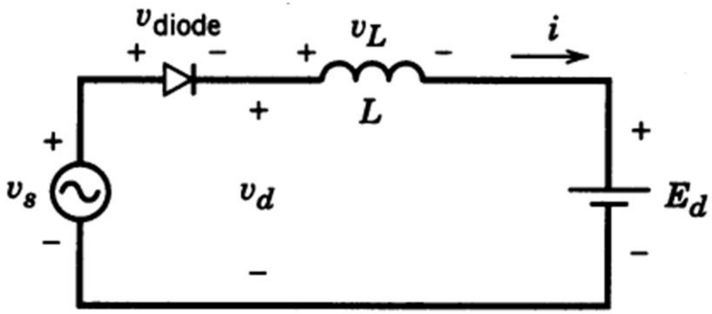


Inductive load, cont

- From t0 to t1
  - Inductor is storing energy
- At t1: vd = vR
  - Inductor starts to output energy
- At t2: negative input voltage, but still non-zero current
- At t3: zero current, diode switch off
- Current even when v_s negative



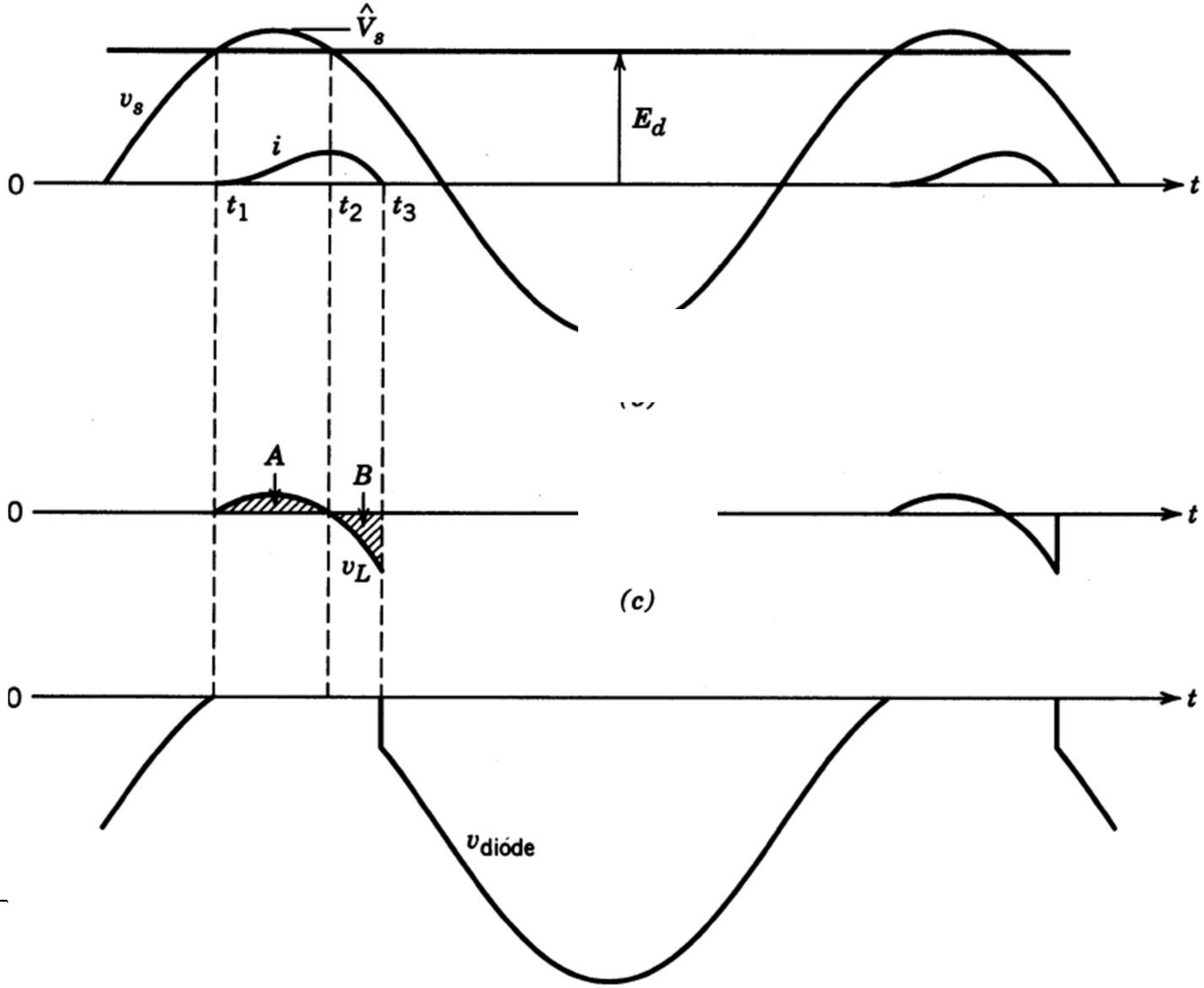
Load with an internal dc voltage



- Similar to load and capacitance on DC output
- Diode turn on when $v_s > E_d$
  - Store energy in L
- I maximum when $v_s = E_d$ after v_s reached its maximum
  - Start energy extract from L after this

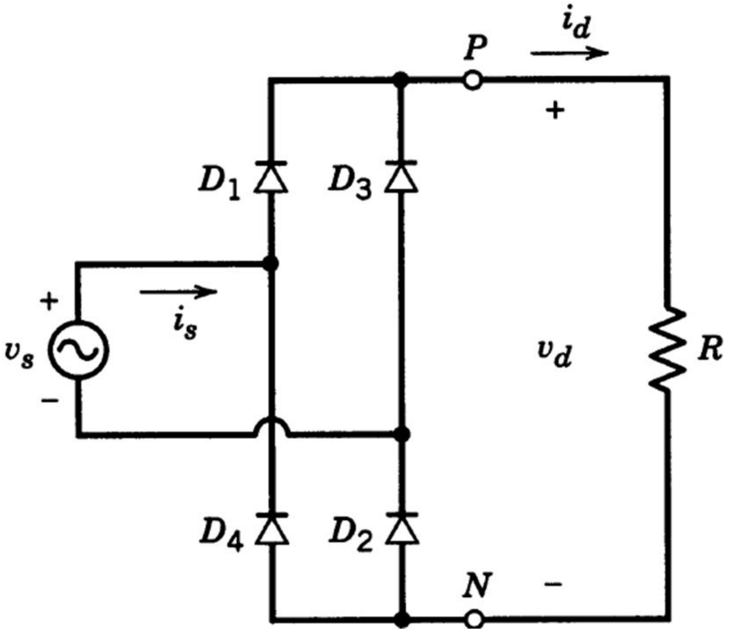
•Load with internal dc voltage

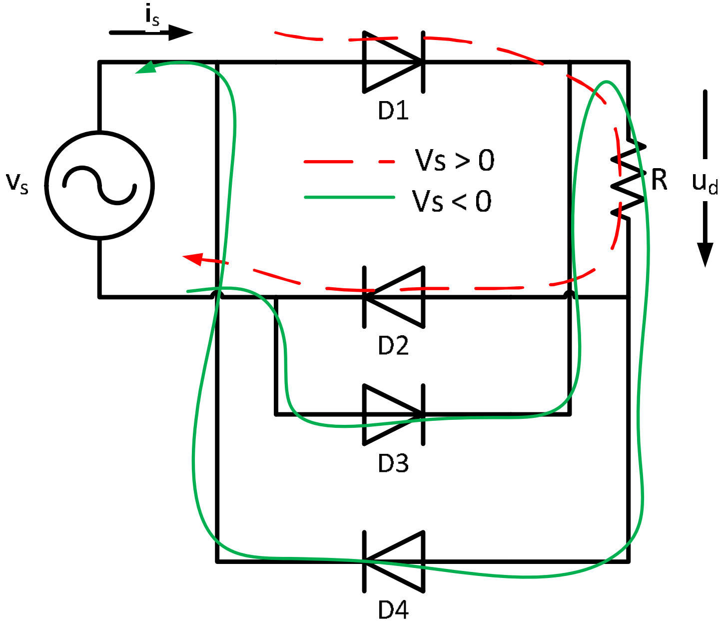
- A = B because steady state (repeated sequence)
- Input current very different from input voltage waveform



Single phase diode bridge rectifier

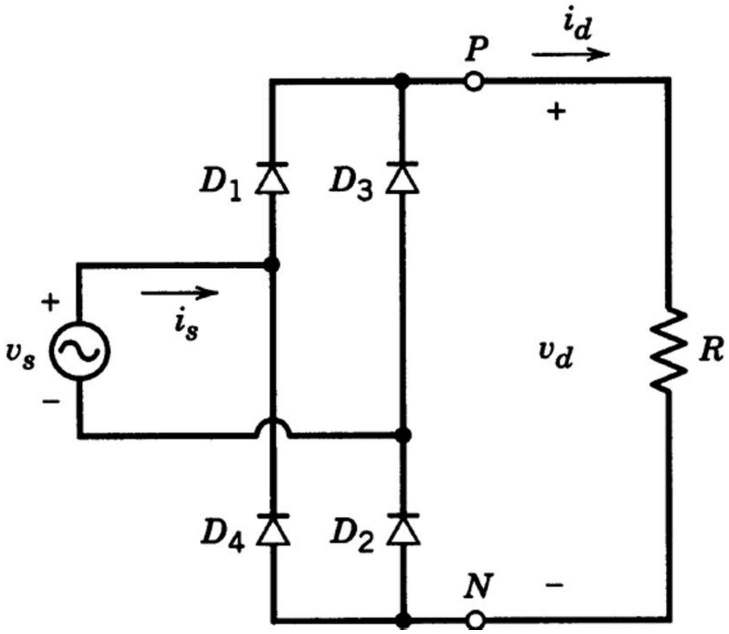
- Two separate circuits defined related to the polarity of v_s

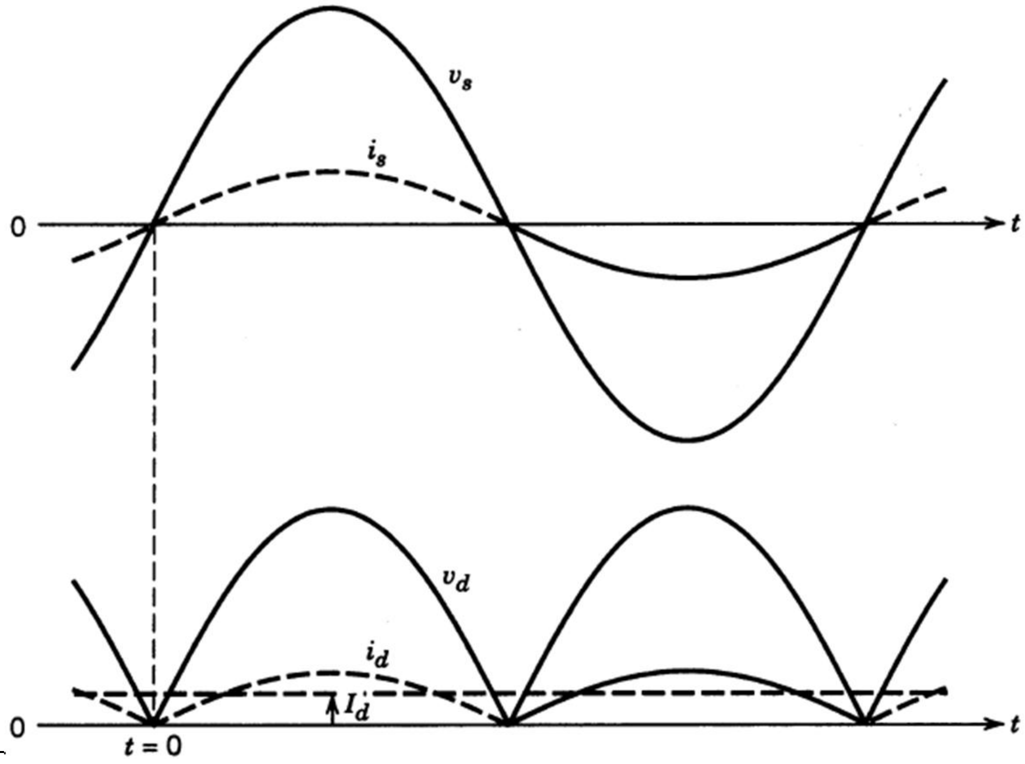




•Idealized circuit, Ls = 0, resistive load

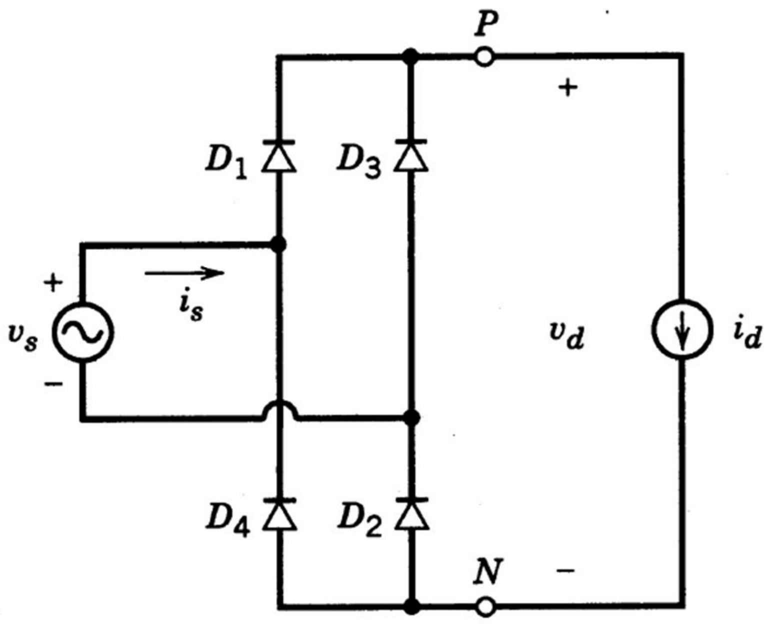
- Used to model power factor corrected rectifier
- Note missing C_d.

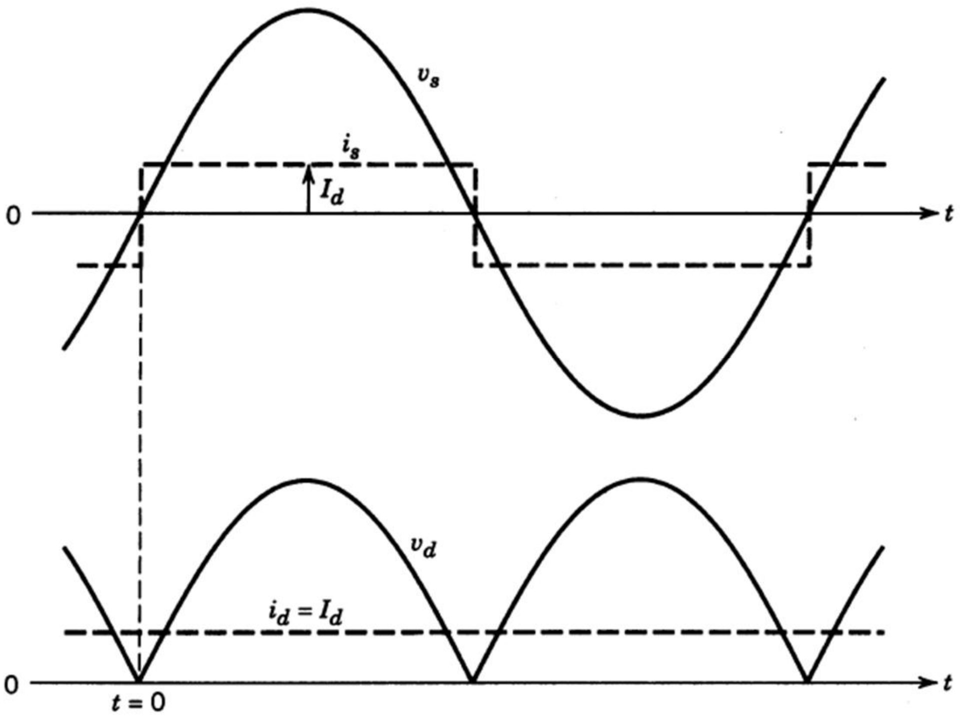




Idealized circuit, Ls = 0, current load

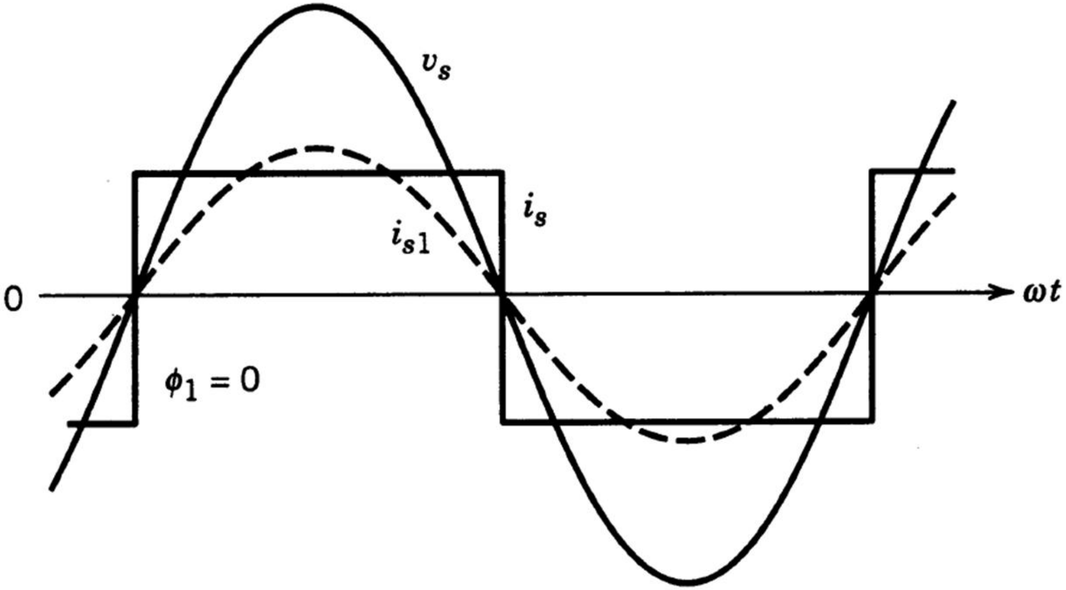
- Simplified model of a big inductance in series on the dc-side
- Same v_d as resistive load

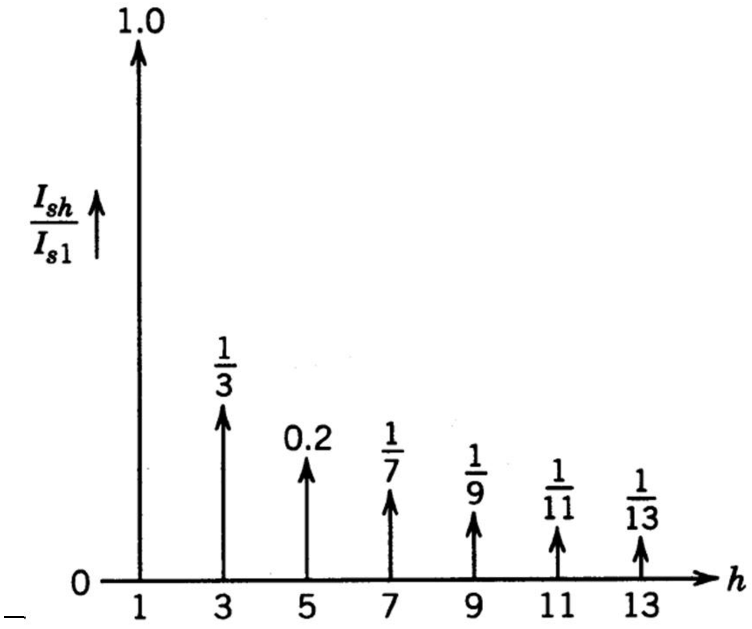




•Idealized circuit, input current

- Input current is a square wave, not sinusoidal
- Fourier analysis gives additional harmonic components {övertoner}





•Fourier analysis

- Non-sinusoidal repeated signal with angular frequency omega

$$f(t) = F_0 + \sum_{h=1}^{\infty} f_h(t) =$$

$$= \frac{1}{2}a_0 + \sum_{h=1}^{\infty} \{a_h \cos(h\omega t) + b_h \sin(h\omega t)\}$$

$$a_h = \frac{1}{\pi}\int_0^{2\pi} f(t)\cos(h\omega t)d(\omega t) h = 0, \ldots, \infty$$

$$b_h = \frac{1}{\pi}\int_0^{2\pi} f(t)\sin(h\omega t)d(\omega t) h = 1, \ldots, \infty$$

•Line current distortion

- Non-sinusoidal currents may give distortion on utility-supply voltage.
- Assume purely sinusoidal voltage at fundamental frequency {grundton}
- Input current is sum of a fundamental plus harmonics {övertoner}
- $$i_s(t) = i_{s1}(t) + \sum_{h\neq 1} i_{sh}(t)$$
- Distortion part is the harmonics (excluding fundamental). In RMS form

$$I_{dis} = \sqrt{\left(\sum_{h\neq 1} I_{sh}^2\right)}$$

•THD, Total Harmonic Distortion

- Distortion on a current waveform

$$\%THD_i = 100 \times \frac{I_{dis}}{I_{s1}} = 100 \times \sqrt{\sum_{h \neq 1} \left(\frac{I_{sh}}{I_{s1}}\right)^2}$$

- Energy in the harmonics compared to the fundamental
- THD can be larger than 1! (> 100%)

•Crest factor

- Comparing peak value (instantaneous) and total rms current

$$Crestfactor = \frac{I_{s,peak}}{I_s}$$

- Peak value may define component ratings

•Power factor for non-sinusoidal wave

- Assume fundamental only sinusoidal voltage with no harmonics
  - Harmonics do not contribute to power due to cross-product integrates to zero => only fundamental rms current used

$$P = V_s I_{s1} \cos\phi$$

- Apparent power
  - Include all harmonics

$$S = V_s I_s$$

- Power factor

$$PF = \frac{P}{S} = \frac{V_s I_{s1} \cos\phi_1}{V_s I_s} = \frac{I_{s1}}{I_s} \cos\phi_1$$

•Displacement Power Factor

- Equals the power factor in case of sinusoidal voltage and current (angle is between fundamental voltage and current)

$$DPF = \cos\phi_1$$

- Combine with previous definitions

$$PF = \frac{I_{s1}}{I_s} DPF$$

$$PF = \frac{1}{\sqrt{1 + THD_i^2}} DPF$$

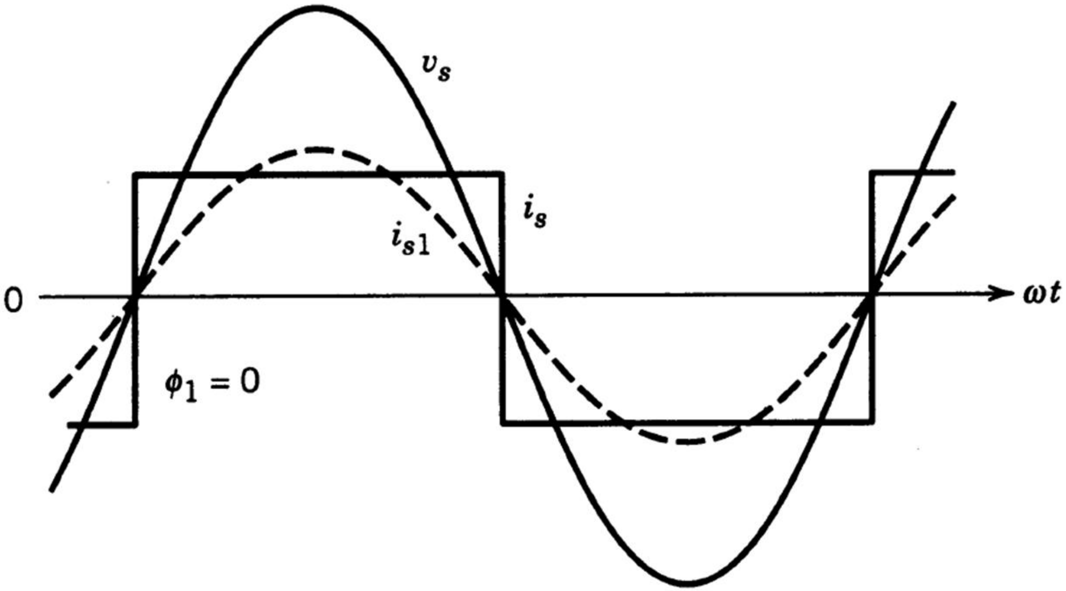
•Idealized circuit, input current

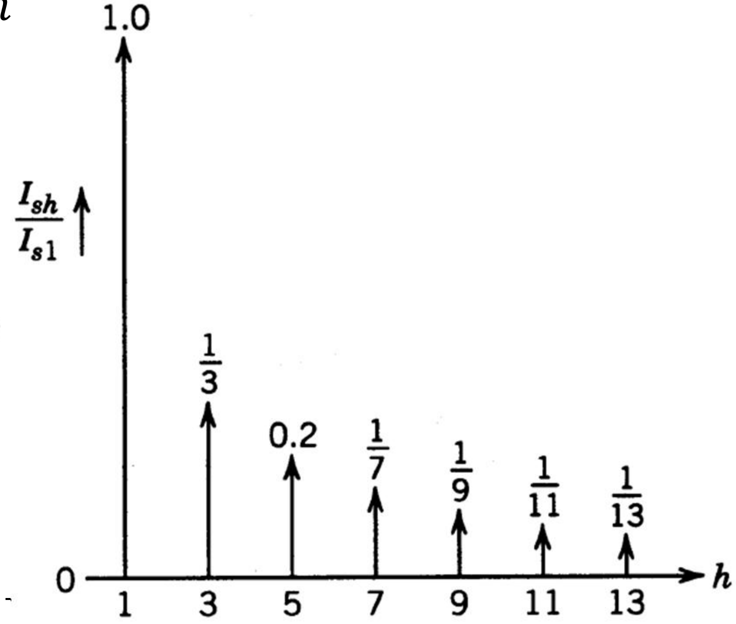
- Fourier analysis gives additional harmonic components
  - Remember calculation uses RMS of Is, Is1 and Id

$$I_{s1} = \frac{2}{\pi}\sqrt{2}I_d = 0.9I_d$$

$$I_{sh} = 0\ for\ even\ harmonics$$

$$I_{sh} = \frac{I_{s1}}{h}\ for\ odd\ harmonics$$





Exercises, lecture 2

5-1, 5-2, 5-3, 5-4, 5-7, 5-14

5-1

5-1 In the basic circuit of Fig. 5-3*a*, V_s = 120 V at 60 Hz, L = 10 mH, and R = 5 Ω. Calculate and plot the current i along with v_s.

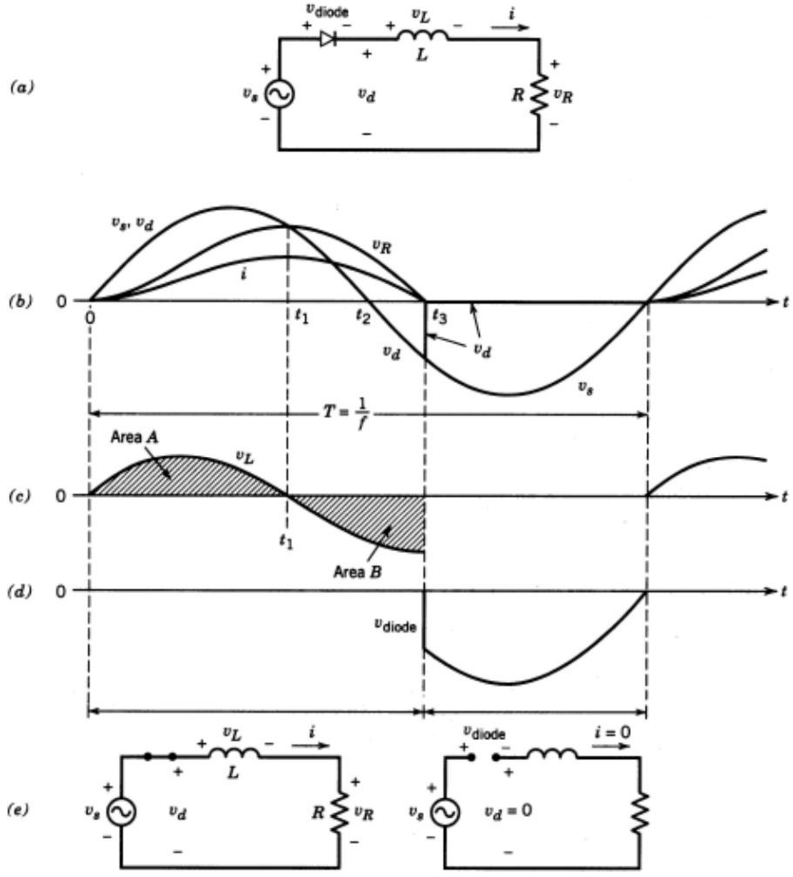


Figure 5-3 Basic rectifier with an inductive load.

5-2

5-2 In the basic circuit of Fig. 5-4*a*, $V_s = 120$ V at 60 Hz, $L = 10$ mH, and $V_d = 150$ V. Calculate and plot the current i

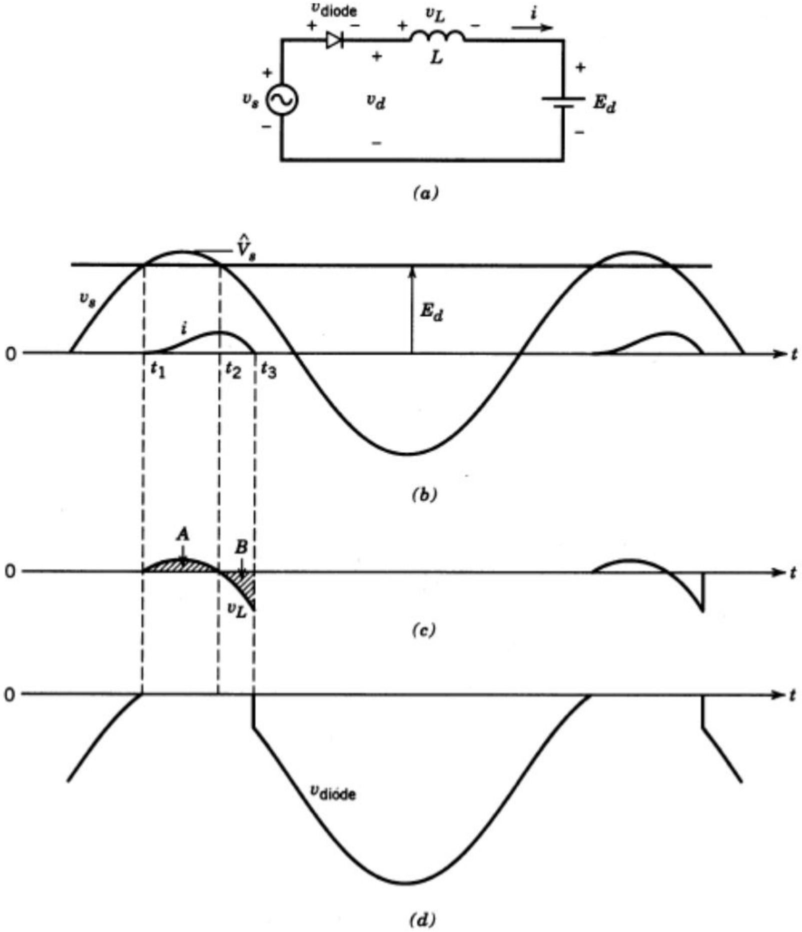
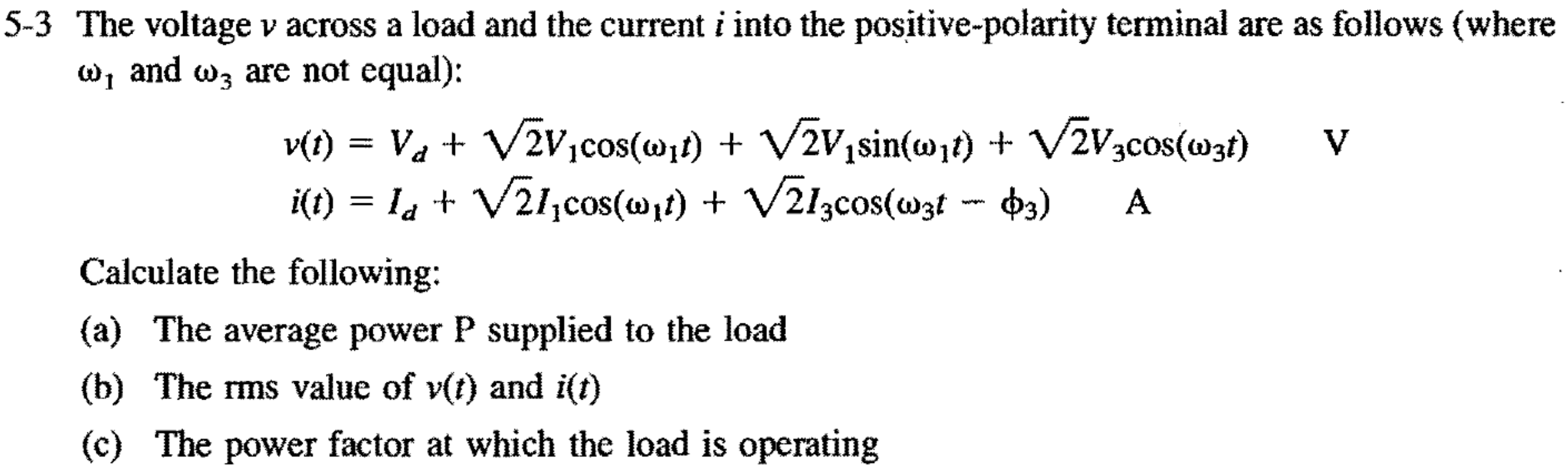


Figure 5-4 Basic rectifier with an internal dc voltage.

5-3



5-3 The voltage v across a load and the current i into the positive-polarity terminal are as follows (where ω_1 and ω_3 are not equal):

$$v(t) = V_d + \sqrt{2}V_1\cos(\omega_1 t) + \sqrt{2}V_1\sin(\omega_1 t) + \sqrt{2}V_3\cos(\omega_3 t) \qquad \text{V}$$
$$i(t) = I_d + \sqrt{2}I_1\cos(\omega_1 t) + \sqrt{2}I_3\cos(\omega_3 t - \phi_3) \qquad \text{A}$$

Calculate the following:

(a) The average power P supplied to the load

(b) The rms value of $v(t)$ and $i(t)$

(c) The power factor at which the load is operating

SINGLE-PHASE RECTIFIERS

5-4 In the single-phase diode rectifier circuit shown in Fig. 5-6*b* with zero L_s and a constant dc current $I_d = 10$ A, calculate the average power supplied to the load:

(a) If v_s is a sinusoidal voltage with $V_s = 120$ V at 60 Hz

(b) If v_s has the pulse waveform shown in Fig. P5-4

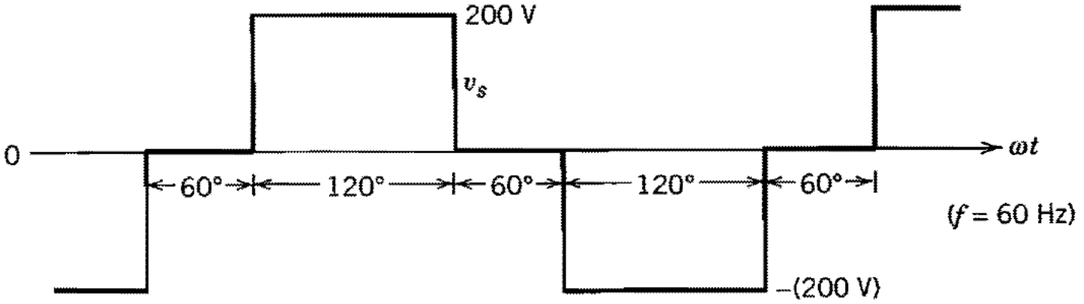
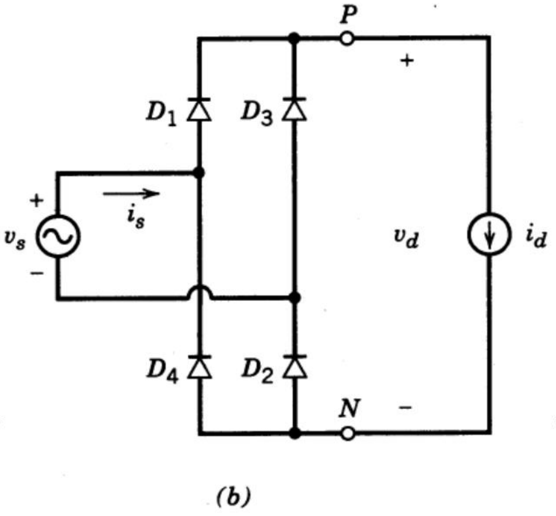


Figure P5-4



5-7 In the single-phase rectifier circuit of Fig. 5-20, assume the ac-side impedance to be negligible. Instead, an inductance L_d is placed between the rectifier output and the filter capacitor. Derive the minimum value of L_d in terms of V_s, ω, and I_d that will result in a continuous i_d assuming that the ripple in v_d is negligible.

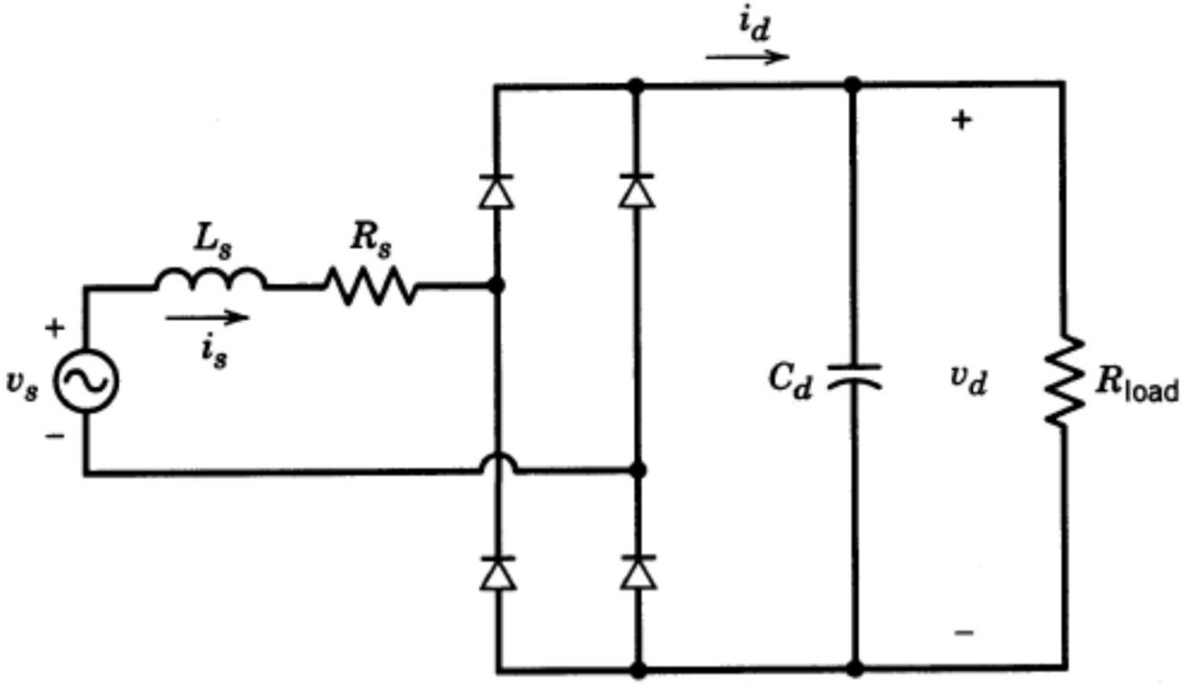
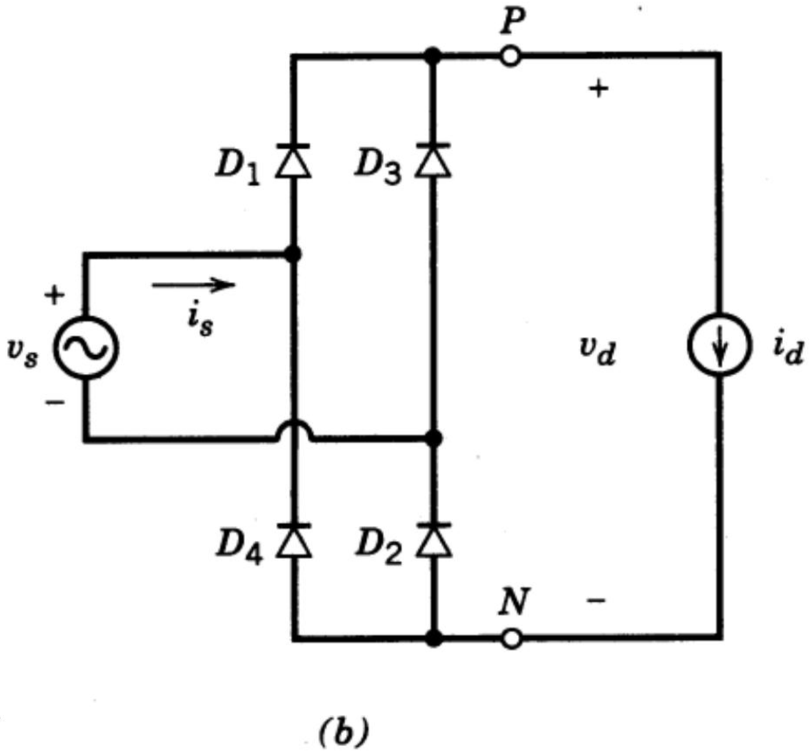


Figure 5-20 Practical diode–bridge rectifier with a filter capacitor.

5-14

- In the single-phase rectifier circuit of Fig. *5-6b* with $i_d = I_d$, obtain the THD, DPF, PF, and CF.



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