Diodes

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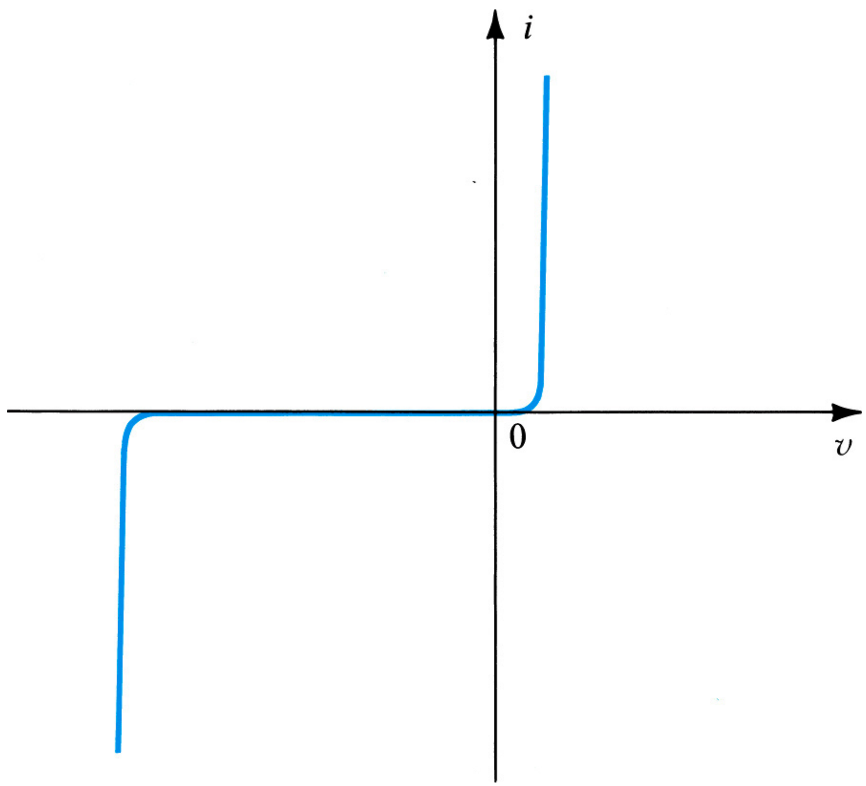
* Most figures and examples are from the course textbook "Microelectronic Circuits" by Adel S. Sedra and Kenneth C. Smith, 6th Edition, © 2010 by Oxford University Press, Inc.

Outline

- Large-signal models & analysis of forward-biased diodes
  - Exponential, Ideal and Constant Voltage-Drop Diode Models
  - Solving by Iteration, or by Graphical Analysis using Load Lines
- Small-signal analysis & the Small-signal Diode Model
- Models for reverse-biased Zener diodes
- Applications of Diodes
  - Voltage Regulation
  - Diode Logic Circuits
  - Limiting & Clamping Circuits
  - DC Restorer and Voltage Doubler Circuits
- Power Supplies
  - Diode rectifiers, Filters, Voltage regulation
- Summary of key concepts

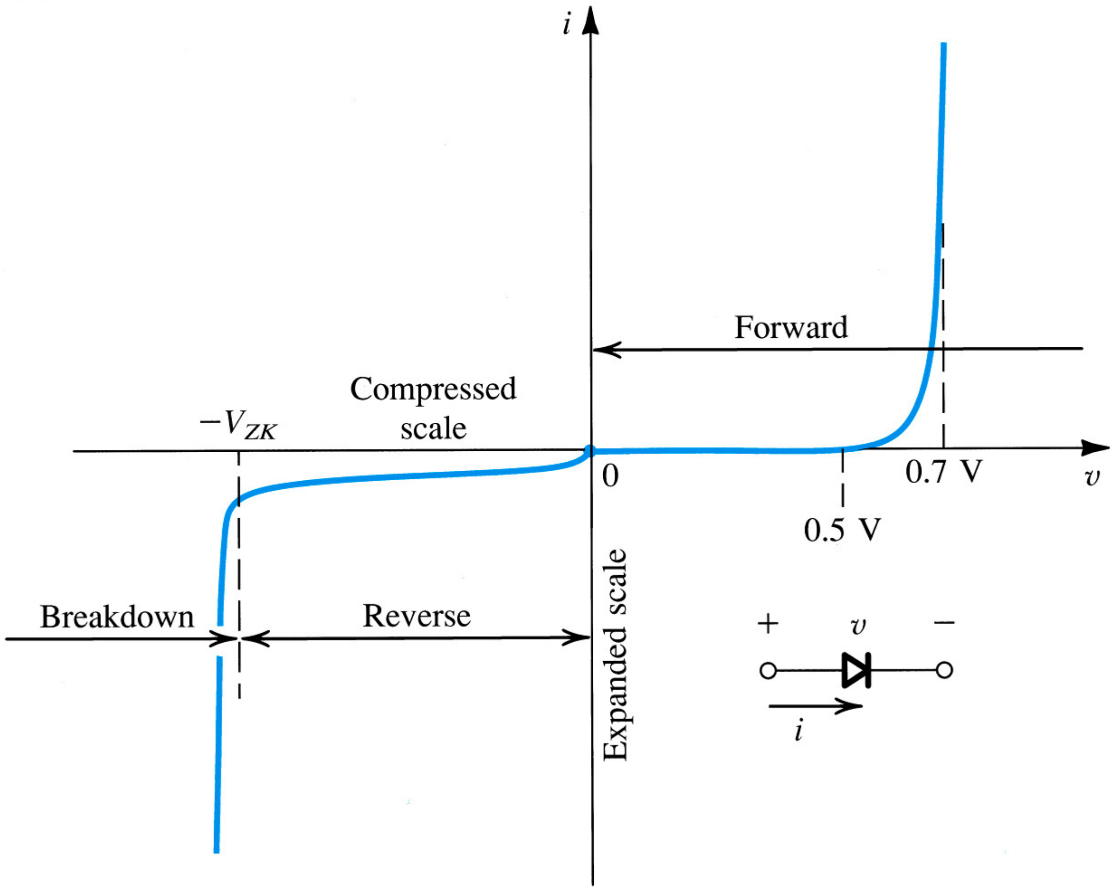
I-V Characteristics of PN Diodes



$$I = I_S\left(e^{V/V_T} - 1\right) \quad where:\ V_T = \frac{kT}{q}$$

- As discussed previously, PN junction **Diodes** conduct current when the junction is forward-biased (Voltage applied on the P-side is > on N-side)
- When reverse-biased, a diode only conducts a small current called the **saturation current, I_S**
- If the reverse bias voltage exceeds the **breakdown voltage**, then current flow increases sharply

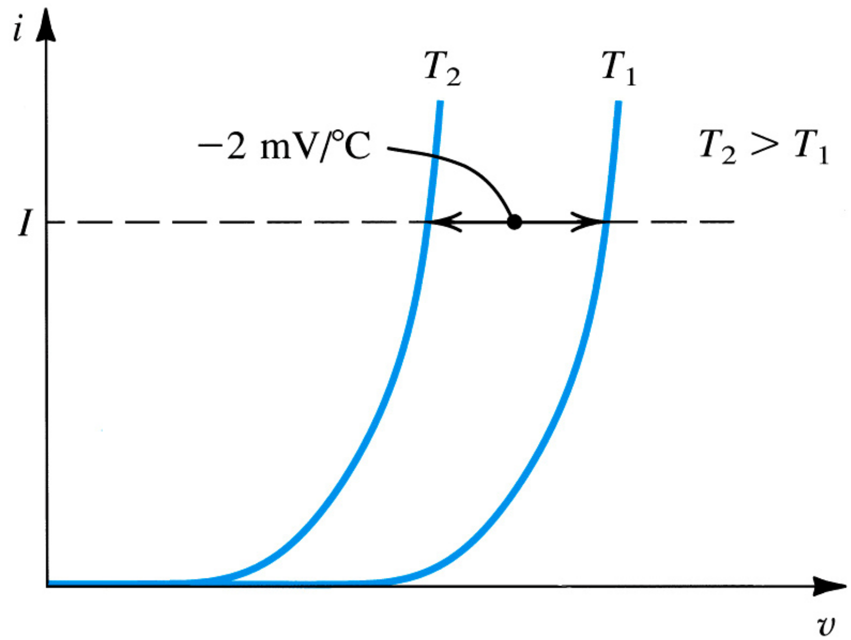
I-V Characteristics of PN Diodes



Note the use of expanded & compressed scales here to better show important details

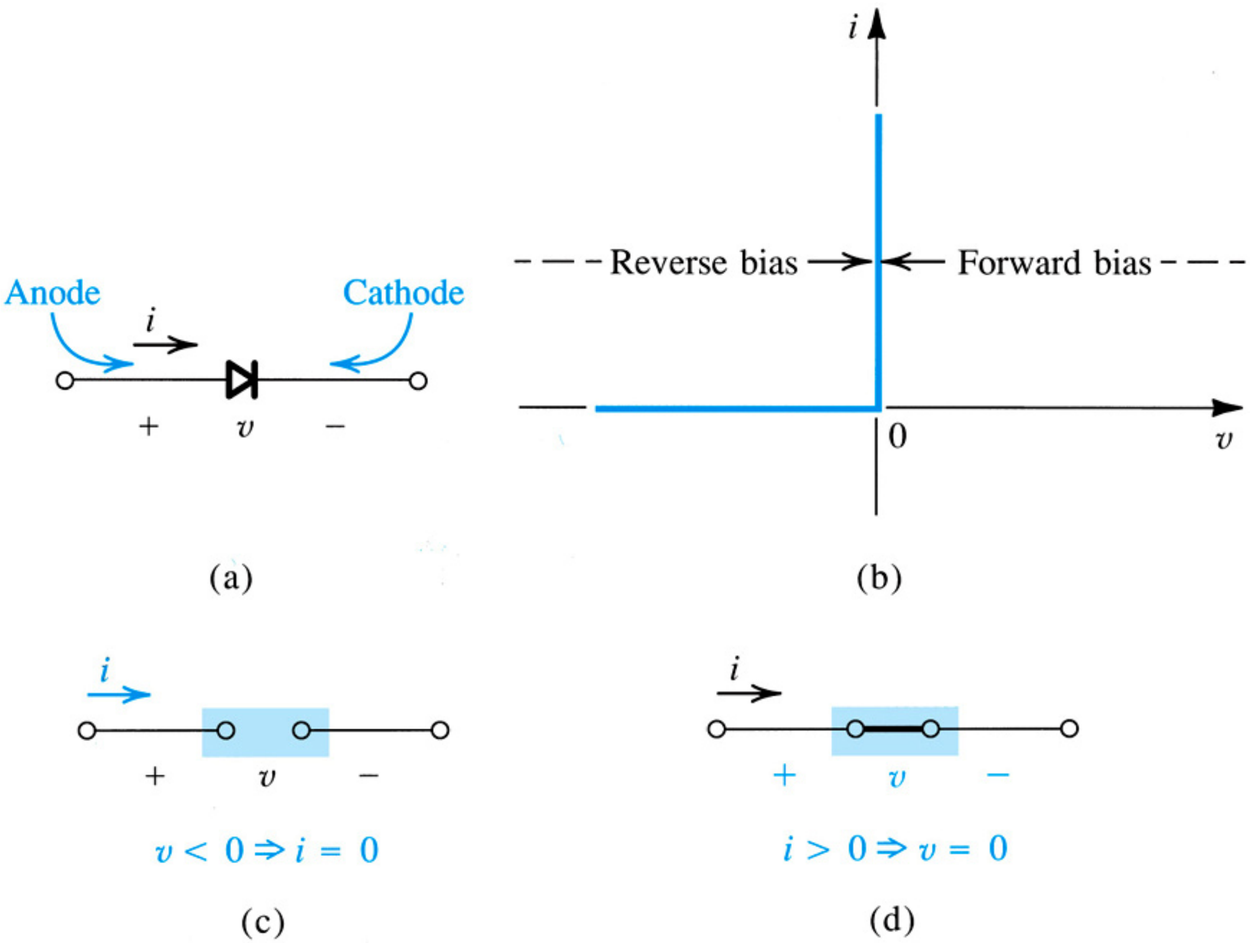
- Silicon diodes "turn on" and start to carry a significant amount of current at a forward bias of ~ 0.5V at 300°K (room temperature)
- As I increases, so does V, but slowly **~60mV/decade of I**
- V across a diode only varies slightly as I increases exponentially!

Temperature Dependence



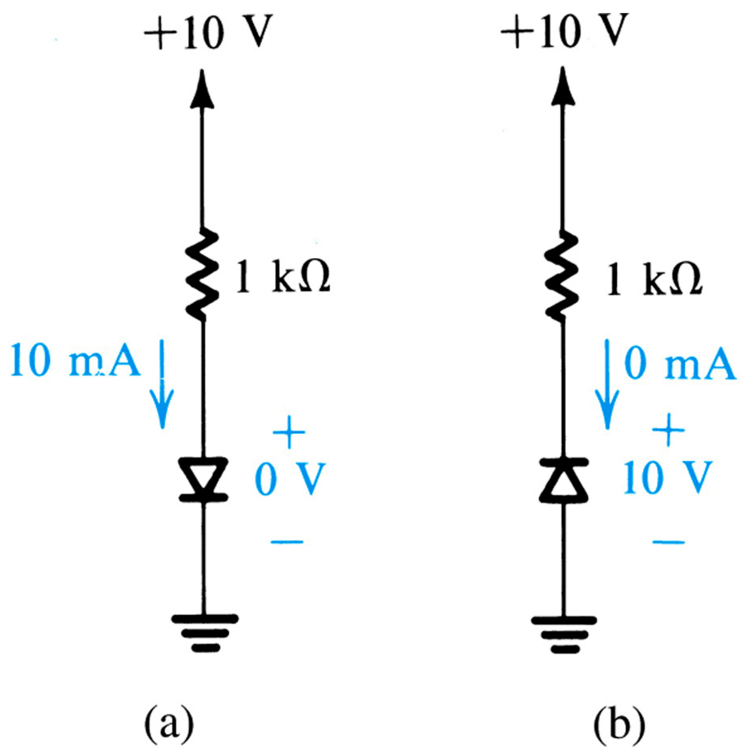
- The bias voltage across a diode which is carrying a constant current drops as temperature goes up!
- V drops by ~ -2mV/°C as temperature increases
- In some applications, this can cause problems with "thermal runaway"
- To avoid these problems, diodes are usually biased with a constant current, <u>not</u> at a constant voltage.

Ideal Diode Model



- The simplest model for a diode is the **Ideal Diode model**
- This models forward-biased diodes as short circuits (V = 0), and reverse-biased diodes as open circuits (I = 0)

Ideal Diode Model in Forward Bias



- For example, the circuit on the left has I = 10mA, since the voltage across the forward-biased diode is assumed to be 0 V so I = 10V / 1kΩ
- The circuit on the right has I = 0, since the reverse-biased diode is assumed to be an open circuit, and the full 10V appears across the reverse-biased diode

<u>To solve these problems :</u>

1st assume diodes are on or off,
2nd analyze the circuit, and
3rd check your assumptions

Example 4.2

Assuming the diodes to be ideal, find the values of I and V in the circuits of Fig. 4.6.

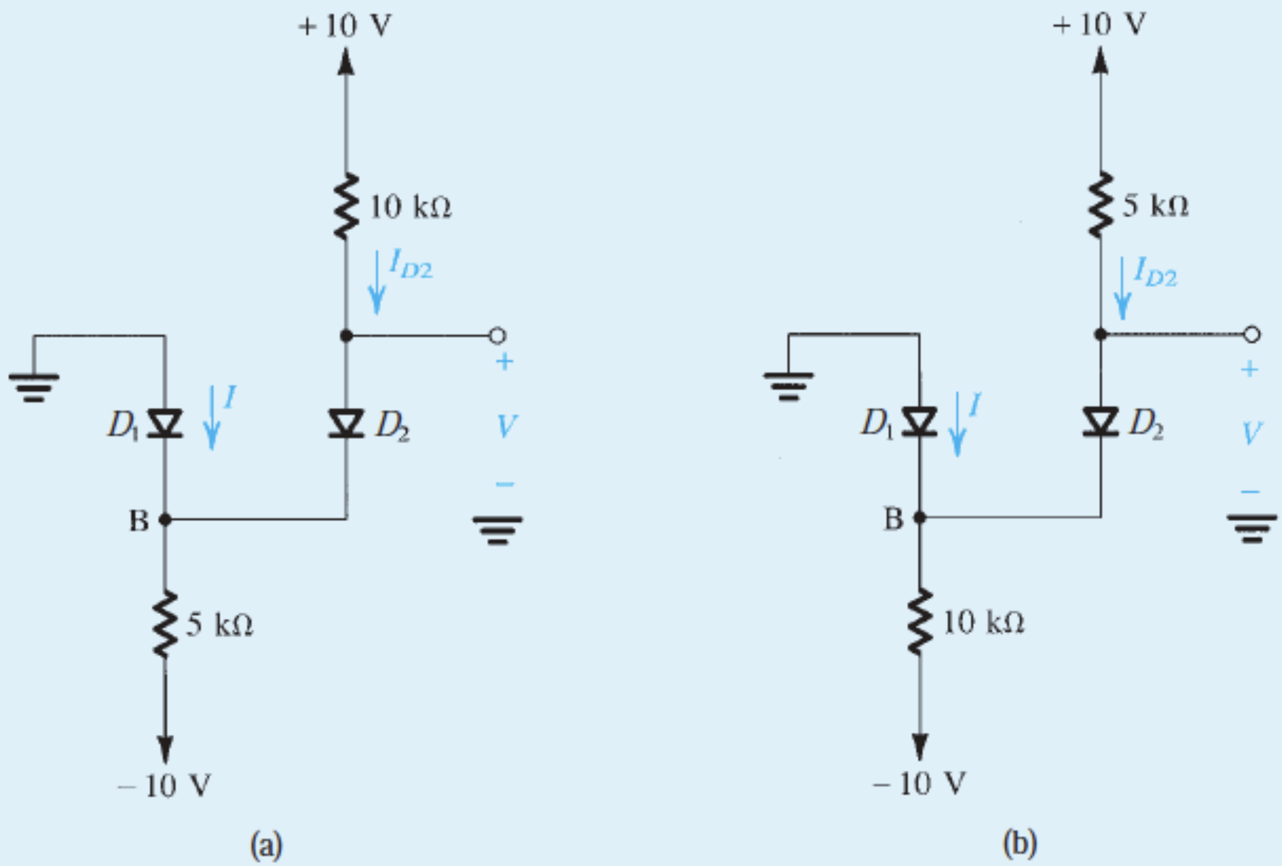


Figure 4.6 Circuits for Example 4.2.

Solution

In these circuits it might not be obvious at first sight whether none, one, or both diodes are conducting. In such a case, *we make a plausible assumption, proceed with the analysis, and then check whether we end up with a consistent solution.* For the circuit in Fig. 4.6(a), we shall assume that both diodes are conducting. It follows that $V_B = 0$ and $V = 0$. The current through D_2 can now be determined from

$$I_{D2} = \frac{10 - 0}{10} = 1 \text{ mA}$$

Writing a node equation at B,

$$I + 1 = \frac{0 - (-10)}{5}$$

results in $I = 1$ mA. Thus D_1 is conducting as originally assumed, and the final result is $I = 1$ mA and $V = 0$ V.

For the circuit in Fig. 4.6(b), if we assume that both diodes are conducting, then $V_B = 0$ and $V = 0$. The current in D_2 is obtained from

$$I_{D2} = \frac{10 - 0}{5} = 2 \text{ mA}$$

The node equation at B is

$$I + 2 = \frac{0 - (-10)}{10}$$

which yields $I = -1$ mA. Since this is not possible, our original assumption is *not* correct. We start again, assuming that D_1 is off and D_2 is on. The current I_{D2} is given by

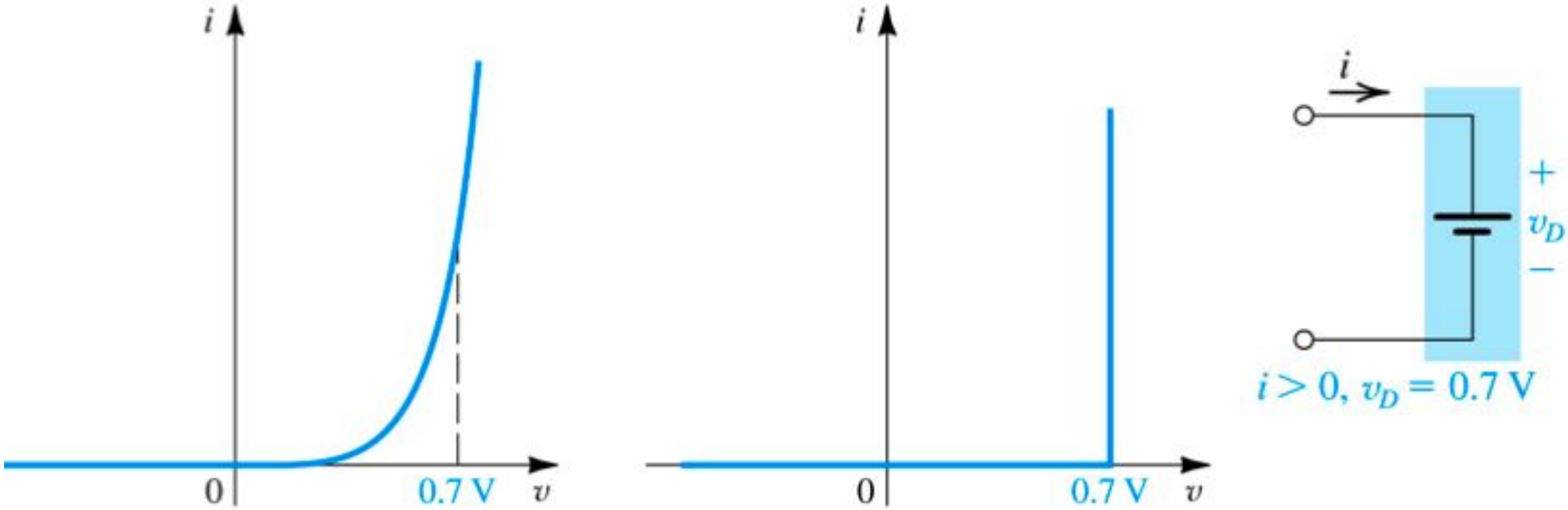
$$I_{D2} = \frac{10 - (-10)}{15} = 1.33 \text{ mA}$$

and the voltage at node B is

$$V_B = -10 + 10 \times 1.33 = +3.3 \text{ V}$$

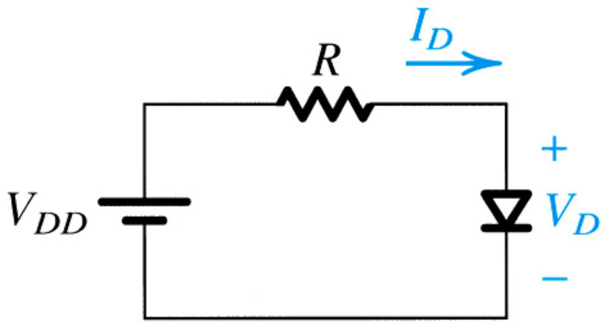
Thus D_1 is reverse biased as assumed, and the final result is $I = 0$ and $V = 3.3$ V.

Constant Voltage Model in Forward Bias



- A better diode model which typically gives more accurate results in circuit analysis is the **Constant Voltage Model**
- This model also assumes the diode is a short circuit when forward-biased, and an open circuit when reverse biased
- The diode is assumed to have **V = 0.7V** across it when on
  - 0.7V is a reasonable value to assume for most diodes

Example using Diode models



For this example use :

V_{DD} = 5 V

R = 1 kΩ

Then find I_D using :

$I_D = (V_{DD} - V_D) / R$

- Using the Ideal Diode model with V_D = 0V when the diode is turned on :

→ I_D = 5V / 1 kΩ = 5mA

- Using the Constant Voltage diode model with V_D = 0.7V when the diode is turned on :

→ I_D = 4.3V / 1 kΩ = 4.3mA

- To get the most accurate value, we must use the exponential equation for I_D

Solving by Iteration

Example 4.4

Determine the current I_D and the diode voltage V_D for the circuit in Fig. 4.10 with $V_{DD} = 5$ V and $R = 1$ kΩ. Assume that the diode has a current of 1 mA at a voltage of 0.7 V.

Solution

To begin the iteration, we assume that $V_D = 0.7$ V and use Eq. (4.7) to determine the current,

$$I_D = \frac{V_{DD} - V_D}{R}$$

$$= \frac{5 - 0.7}{1} = 4.3 \text{ mA}$$

$$I_D = I_S\left(e^{V_D/V_T} - 1\right) \approx I_S e^{V_D/V_T} \Rightarrow \boxed{V_D \approx V_T \ln\left(I_D/I_S\right)} \; with: \; V_T = \frac{kT}{q}$$

It was given that I_D = 1mA at V_D = 0.7V, so we can find I_S :

$$I_S \approx I_D e^{-V_D/V_T} \Rightarrow I_S \approx 10^{-3} e^{-0.7V/0.026V} = 2x10^{-15} A = 2 fA$$

Solving by Iteration

Procedure to solve for I_D by iteration :

1. "Guess" a value for I_D
2. Solve for V_D using $V_D = V_T \ln (I_D/I_S)$
3. Solve for I_D using $I_D = (V_{DD} – V_D) / R$
4. Repeat Steps 1-3, using your new value of I_D as the next "guess"
5. Continue until the values for I_D converge

Example :

Guess 1: $I_D = 4.3000000\text{mA} \rightarrow V_D = 738.309\text{mV} \rightarrow I_D = 4.2616913\text{mA}$

Guess 2: $I_D = 4.2616913\text{mA} \rightarrow V_D = 738.076\text{mV} \rightarrow I_D = 4.2619240\text{mA}$

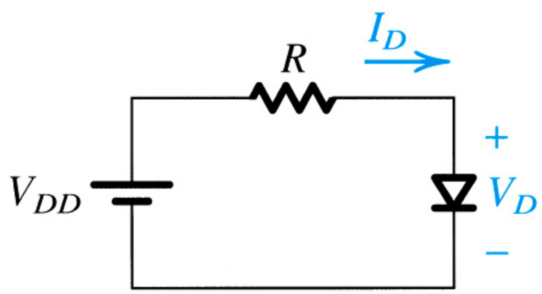
Guess 3: $I_D = 4.2619240\text{mA} \rightarrow V_D = 738.077\text{mV} \rightarrow I_D = 4.2619225\text{mA}$

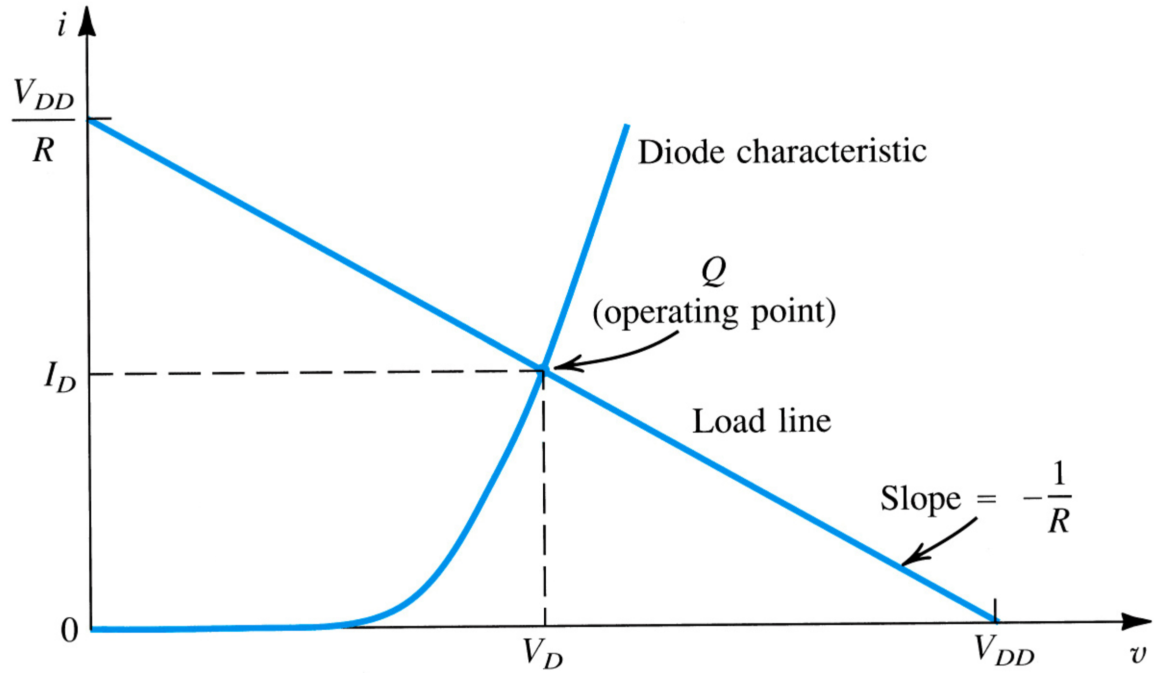
Guess 4: $I_D = 4.2619225\text{mA} \rightarrow V_D = 738.077\text{mV} \rightarrow I_D = 4.2619225\text{mA}$

The result converged after only 4 iterations due to a good 1st guess. ☺

Note the use of the slowly varying ln function to aid convergence!

Graphical Analysis using Load Lines





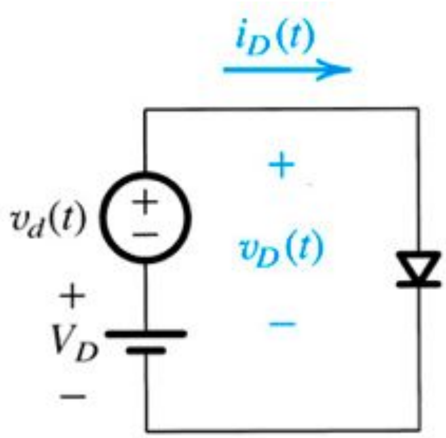
2 equations to solve :

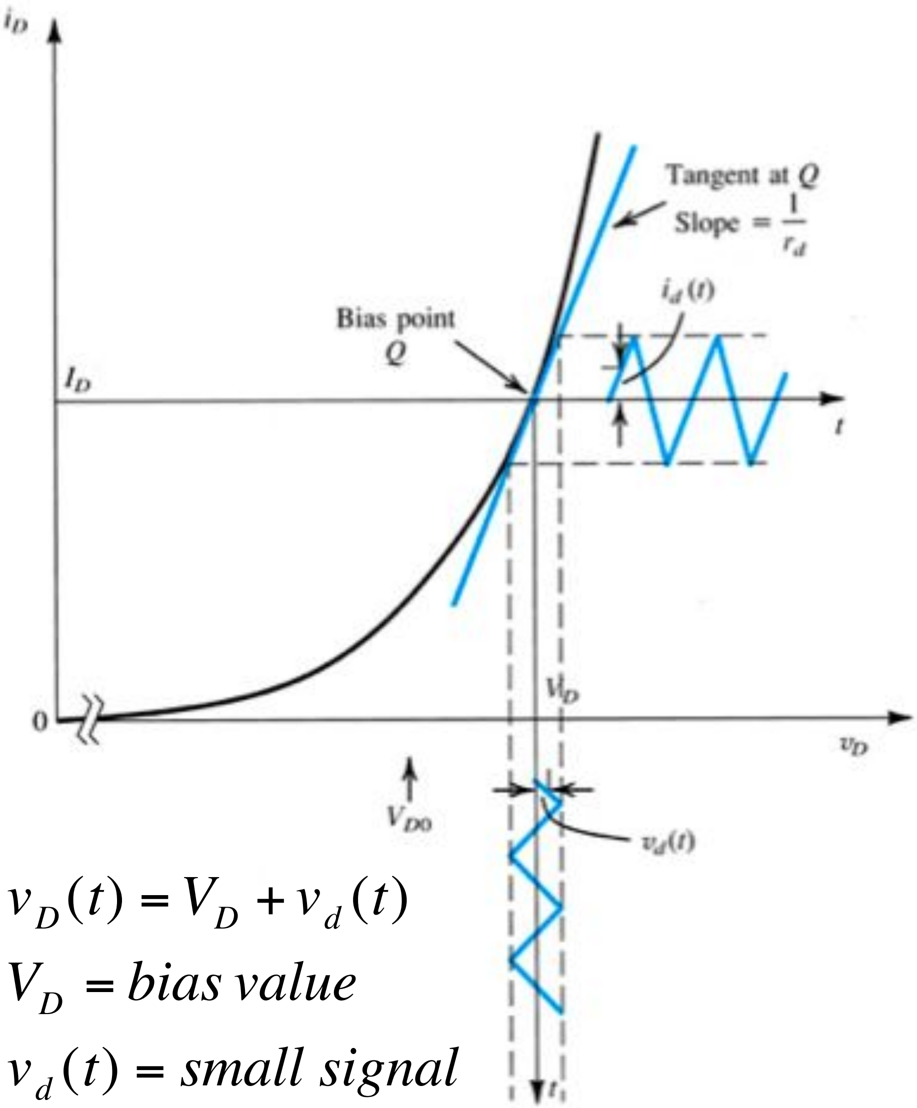
$$I_D = \left(V_{DD} - V_D\right)/R$$

$$I_D = I_S\left(e^{V_D/V_T} - 1\right)$$

- Another way to solve this nonlinear set of simultaneous equations is graphically, by plotting a **Load line** for the circuit on a plot of the diode I-V characteristic curve
  - Where the 2 curves cross is the solution! Called the **Q-point**
  - Can use any 2 points to plot the Load line (Not just V_{DD}/R !)

Small-Signal Analysis





- Linear circuit analysis techniques such as superposition can be used for small variations around a bias point

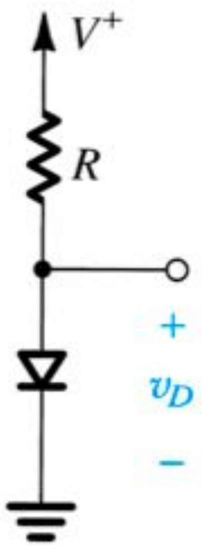
A small enough piece of anything nonlinear looks linear!

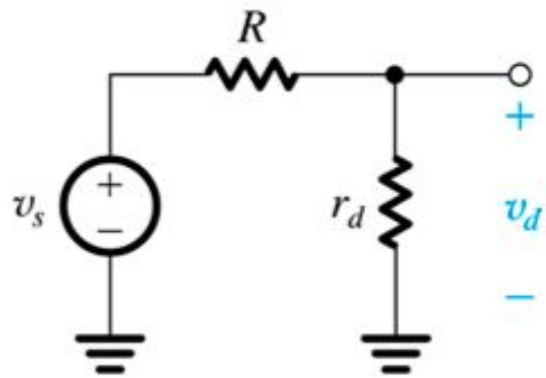
$$v_D(t) = V_D + v_d(t)$$

$$V_D = bias\ value$$

$$v_d(t) = small\ signal$$

Small-Signal Diode Model





Small-signal equivalent circuit

<u>Small-signal diode resistance :</u>

$$g_d = \frac{\partial i_D}{\partial v_D} \text{ at the bias point}$$

$$\Rightarrow \boxed{r_d = \frac{1}{g_d} = \frac{V_T}{I_D}}$$

- It is often convenient to analyze a nonlinear circuit for small variations around a bias point. (aka "Q-point")
  - Can use linear circuit analysis methods, like voltage division
- To do this, we must first find **r_d , the small-signal resistance** of the diode
- Then we can draw the **small-signal equivalent circuit**, and analyze it using standard linear circuit analysis methods.

Example 4.5

Consider the circuit shown in Fig. 4.14(a) for the case in which $R = 10\ \text{k}\Omega$. The power supply V^+ has a dc value of 10 V on which is superimposed a 60-Hz sinusoid of 1-V peak amplitude. (This "signal" component of the power-supply voltage is an imperfection in the power-supply design. It is known as the **power-supply ripple**. More on this later.) Calculate both the dc voltage of the diode and the amplitude of the sine-wave signal appearing across it. Assume the diode to have a 0.7-V drop at 1-mA current.

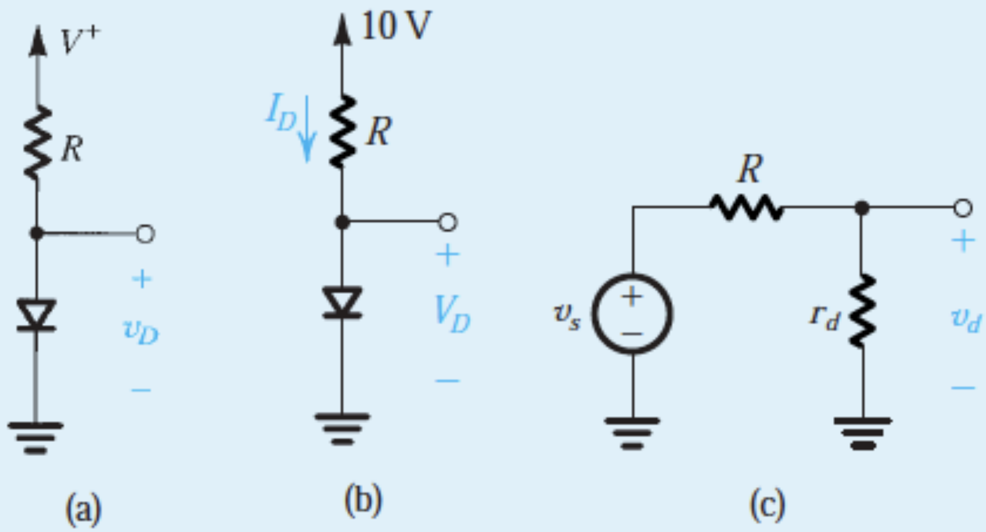


Figure 4.14 **(a)** Circuit for Example 4.5. **(b)** Circuit for calculating the dc operating point. **(c)** Small-signal equivalent circuit.

Solution

Considering dc quantities only, we assume $V_D \simeq 0.7$ V and calculate the diode dc current

$$I_D = \frac{10 - 0.7}{10} = 0.93 \text{ mA}$$

Since this value is very close to 1 mA, the diode voltage will be very close to the assumed value of 0.7 V. At this operating point, the diode incremental resistance r_d is

$$r_d = \frac{V_T}{I_D} = \frac{25}{0.93} = 26.9 \ \Omega$$

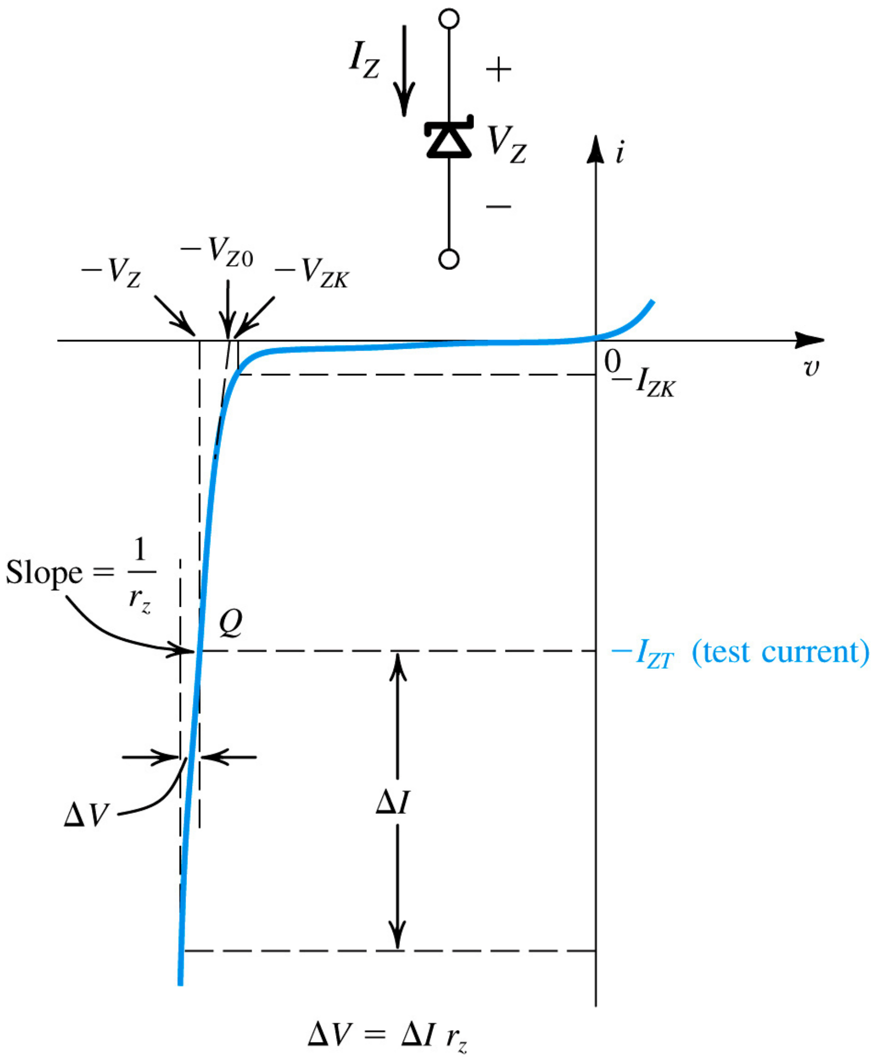
The signal voltage across the diode can be found from the small-signal equivalent circuit in Fig. 4.14(c). Here v_s denotes the 60-Hz 1-V peak sinusoidal component of V^+, and v_d is the corresponding signal across the diode. Using the voltage-divider rule provides the peak amplitude of v_d as follows:

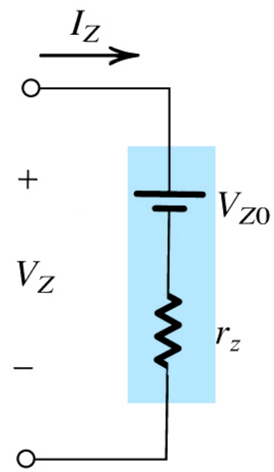
$$v_d \text{ (peak)} = \hat{V}_s \frac{r_d}{R + r_d}$$

$$= 1 \frac{0.0269}{10 + 0.0269} = 2.68 \text{ mV}$$

Finally we note that since this value is quite small, our use of the small-signal model of the diode is justified.

Reverse-biased Zener Diode Model





$$g_Z = \frac{\partial i_Z}{\partial v_Z}\ \textit{at the bias point}$$

$$\Rightarrow \boxed{r_Z = \frac{1}{g_Z} = \frac{1}{Slope}}$$

$$and\ \boxed{V_Z = V_{Z0} + I_Z r_Z}$$

- Zener diodes are diodes intentionally operated in the reverse-breakdown region
- Used as voltage references
- Modeled as a DC battery in series with a small-signal **incremental resistance**, r_Z

Voltage Regulation using Diodes

Example 4.6

Consider the circuit shown in Fig. 4.15. A string of three diodes is used to provide a constant voltage of about 2.1 V. We want to calculate the percentage change in this regulated voltage caused by (a) a ±10% change in the power-supply voltage and (b) connection of a 1-kΩ load resistance.

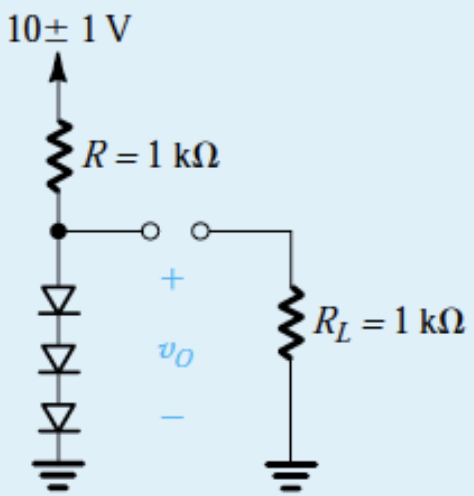


Figure 4.15 Circuit for Example 4.6.

Solution

With no load, the nominal value of the current in the diode string is given by

$$I = \frac{10 - 2.1}{1} = 7.9 \text{ mA}$$

Thus each diode will have an incremental resistance of

$$r_d = \frac{V_T}{I}$$

Thus,

$$r_d = \frac{25}{7.9} = 3.2\ \Omega$$

The three diodes in series will have a total incremental resistance of

$$r = 3r_d = 9.6\ \Omega$$

This resistance, along with the resistance R, forms a voltage divider whose ratio can be used to calculate the change in output voltage due to a ±10% (i.e., ±1-V) change in supply voltage. Thus the peak-to-peak change in output voltage will be

$$\Delta v_O = 2\frac{r}{r+R} = 2\frac{0.0096}{0.0096+1} = 19\ \text{mV peak-to-peak}$$

That is, corresponding to the ±1-V (±10%) change in supply voltage, the output voltage will change by ±9.5 mV or ±0.5%. Since this implies a change of about ±3.2 mV per diode, our use of the small-signal model is justified.

When a load resistance of 1 kΩ is connected across the diode string, it draws a current of approximately 2.1 mA. Thus the current in the diodes decreases by 2.1 mA, resulting in a decrease in voltage across the diode string given by

$$\Delta v_O = -2.1 \times r = -2.1 \times 9.6 = -20\ \text{mV}$$

Since this implies that the voltage across each diode decreases by about 6.7 mV, our use of the small-signal model is not entirely justified. Nevertheless, a detailed calculation of the voltage change using the exponential model results in $\Delta v_O = -23$ mV, which is not too different from the approximate value obtained using the incremental model.

Example 4.7

The 6.8-V zener diode in the circuit of Fig. 4.19(a) is specified to have $V_Z = 6.8$ V at $I_Z = 5$ mA, $r_z = 20\ \Omega$, and $I_{ZK} = 0.2$ mA. The supply voltage V^+ is nominally 10 V but can vary by ±1 V.

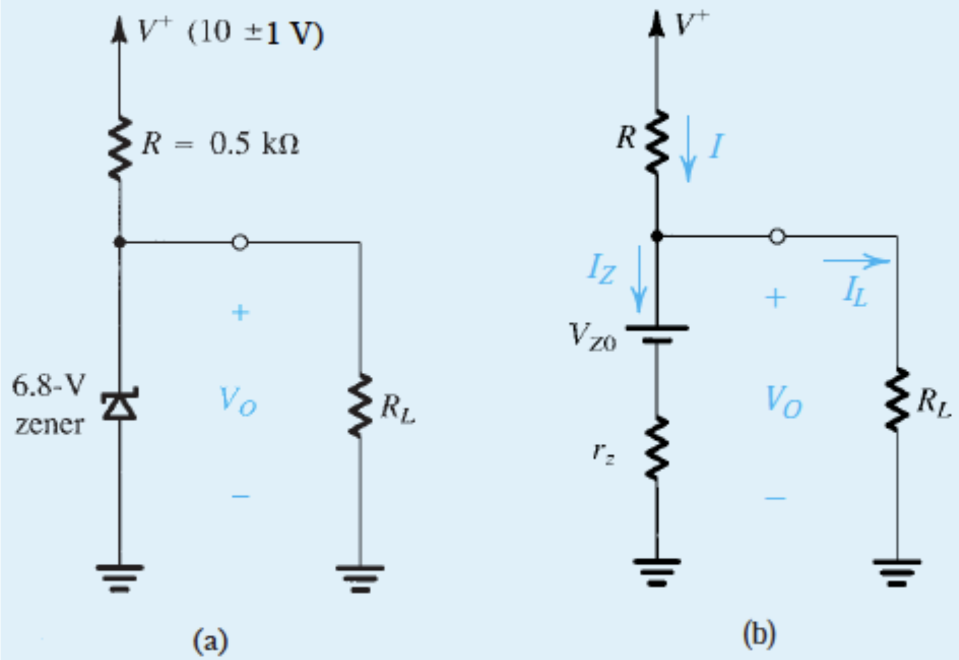


Figure 4.19 **(a)** Circuit for Example 4.7. **(b)** The circuit with the zener diode replaced with its equivalent circuit model.

(a) Find V_O with no load and with V^+ at its nominal value.
(b) Find the change in V_O resulting from the ±1-V change in V^+. Note that $(\Delta V_O/\Delta V^+)$, usually expressed in mV/V, is known as **line regulation**.
(c) Find the change in V_O resulting from connecting a load resistance R_L that draws a current $I_L =$ 1 mA, and hence find the **load regulation** $(\Delta V_O/\Delta I_L)$ in mV/mA.

Solution

First we must determine the value of the parameter V_{Z0} of the zener diode model. Substituting $V_Z = 6.8$ V, $I_Z = 5$ mA, and $r_z = 20\ \Omega$ in Eq. (4.20) yields $V_{Z0} = 6.7$ V. Figure 4.19(b) shows the circuit with the zener diode replaced with its model.

(a) With no load connected, the current through the zener is given by

$$I_Z = I = \frac{V^+ - V_{Z0}}{R + r_z}$$

$$= \frac{10 - 6.7}{0.5 + 0.02} = 6.35 \text{ mA}$$

$$V_Z = V_{Z0} + r_z I_Z$$

Thus,

$$V_O = V_{Z0} + I_Z r_z$$

$$= 6.7 + 6.35 \times 0.02 = 6.83 \text{ V}$$

(b) For a ±1-V change in V^+, the change in output voltage can be found from

$$\Delta V_O = \Delta V^+ \frac{r_z}{R + r_z}$$

$$= \pm 1 \times \frac{20}{500 + 20} = \pm 38.5 \text{ mV}$$

Thus,

$$\text{Line regulation} = 38.5 \text{ mV/V}$$

Line regulation can also be expressed in percent

(c) When a load resistance R_L that draws a load current $I_L = 1$ mA is connected, the zener current will decrease by 1 mA. The corresponding change in zener voltage can be found from

$$\Delta V_O = r_z \Delta I_Z$$

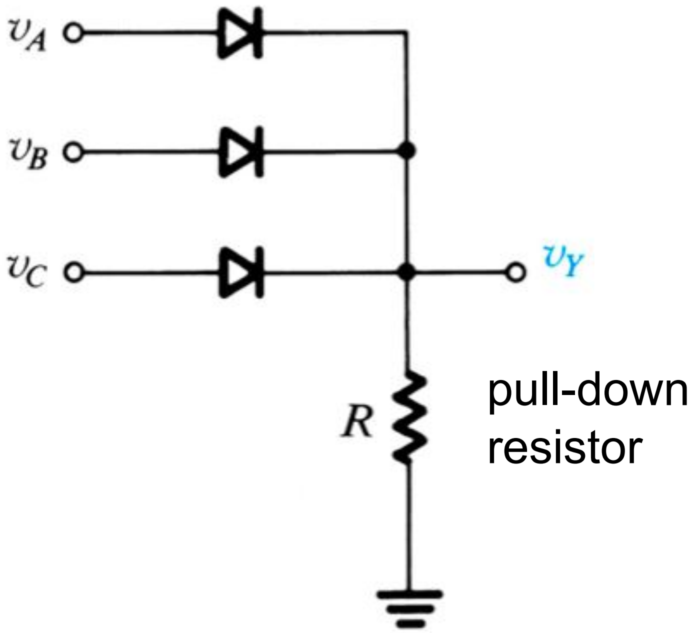
$$= 20 \times -1 = -20 \text{ mV}$$

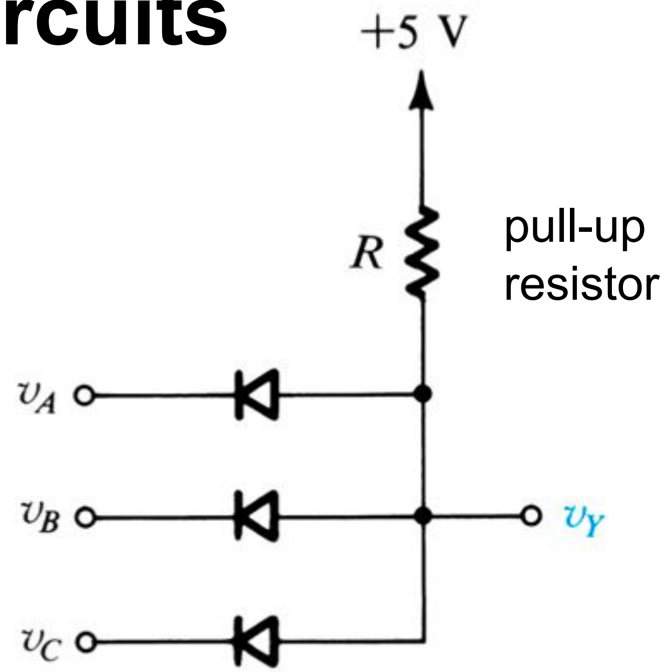
Thus the load regulation is

$$\text{Load regulation} \equiv \frac{\Delta V_O}{\Delta I_L} = -20 \text{ mV/mA}$$

Load regulation can also be expressed in percent

Diode Logic Circuits

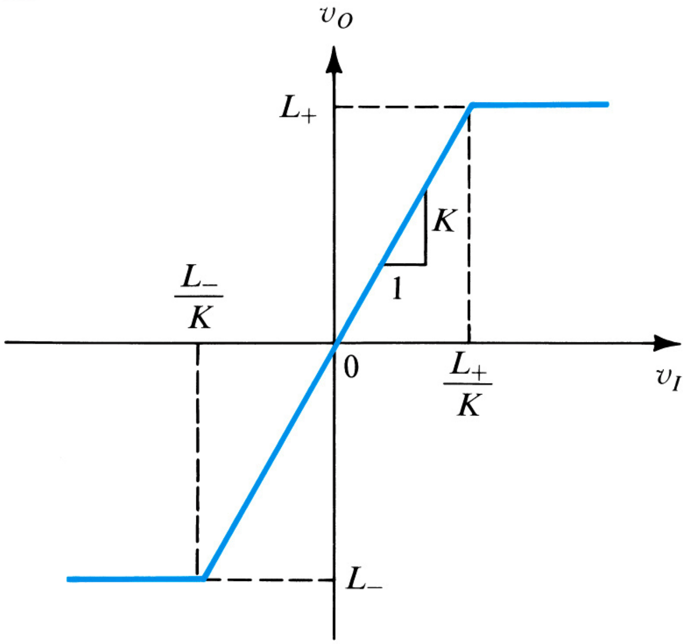


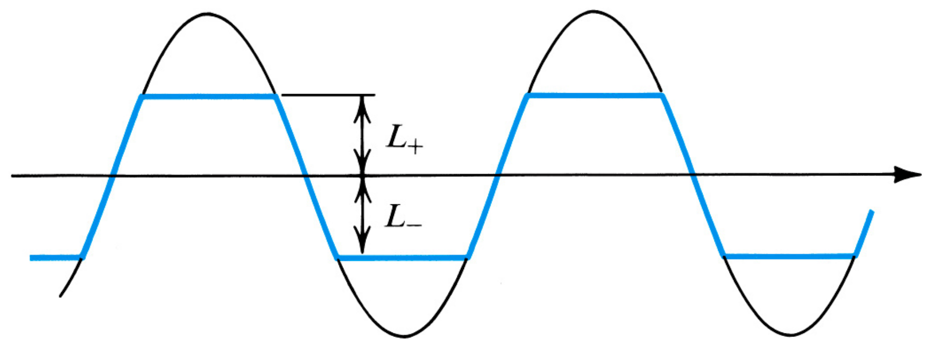


- Diodes can also be used to create simple logic circuits
  - **RDL = Resistor-Diode Logic**
- RDL is an old logic family, seldom used now since it doesn't amplify the signal

- The gate on the left is an OR gate, since the output is high when any input is high
- The gate on the left is an AND gate, since the output is low when any input is low

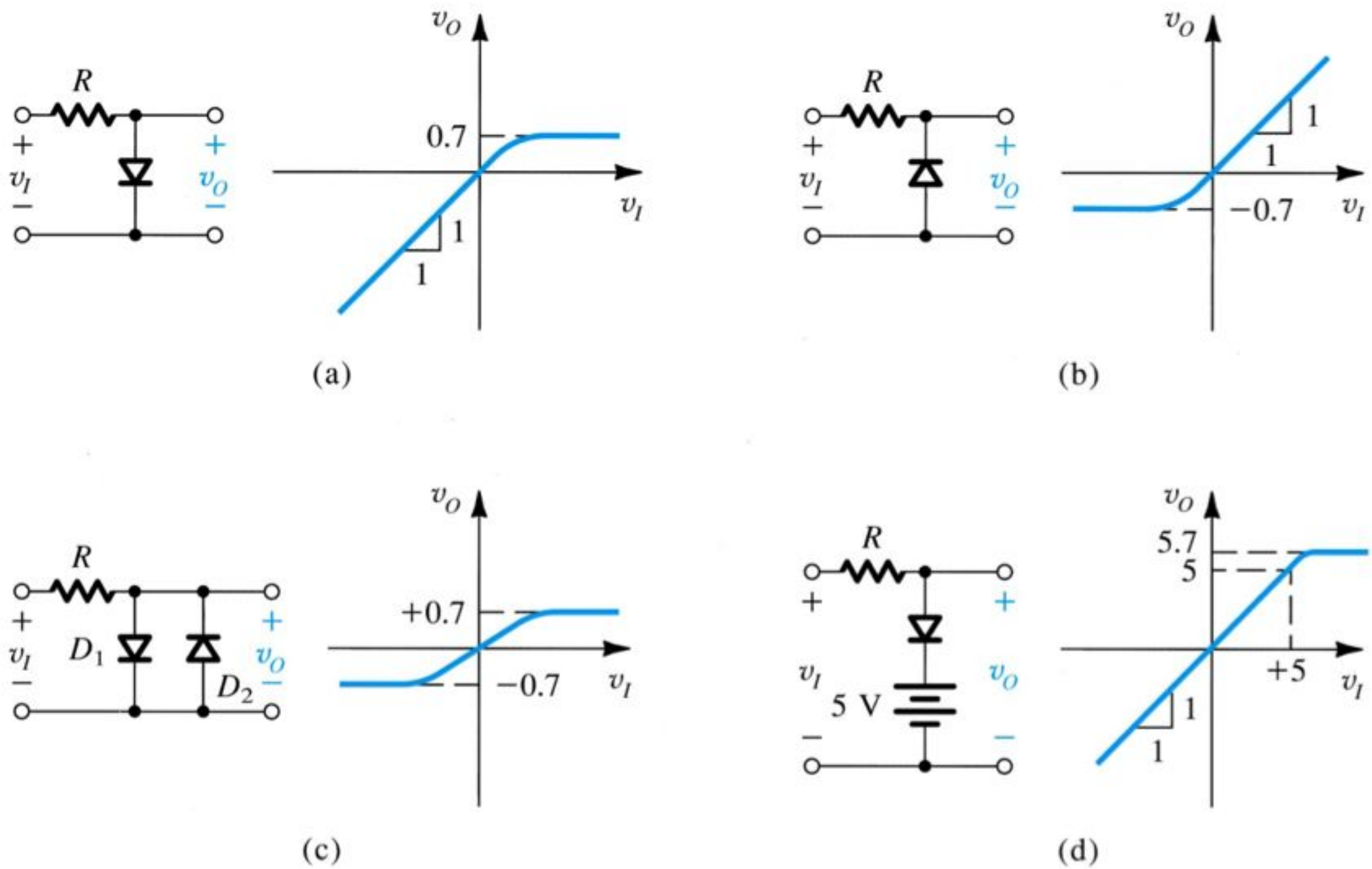
Limiter Circuits



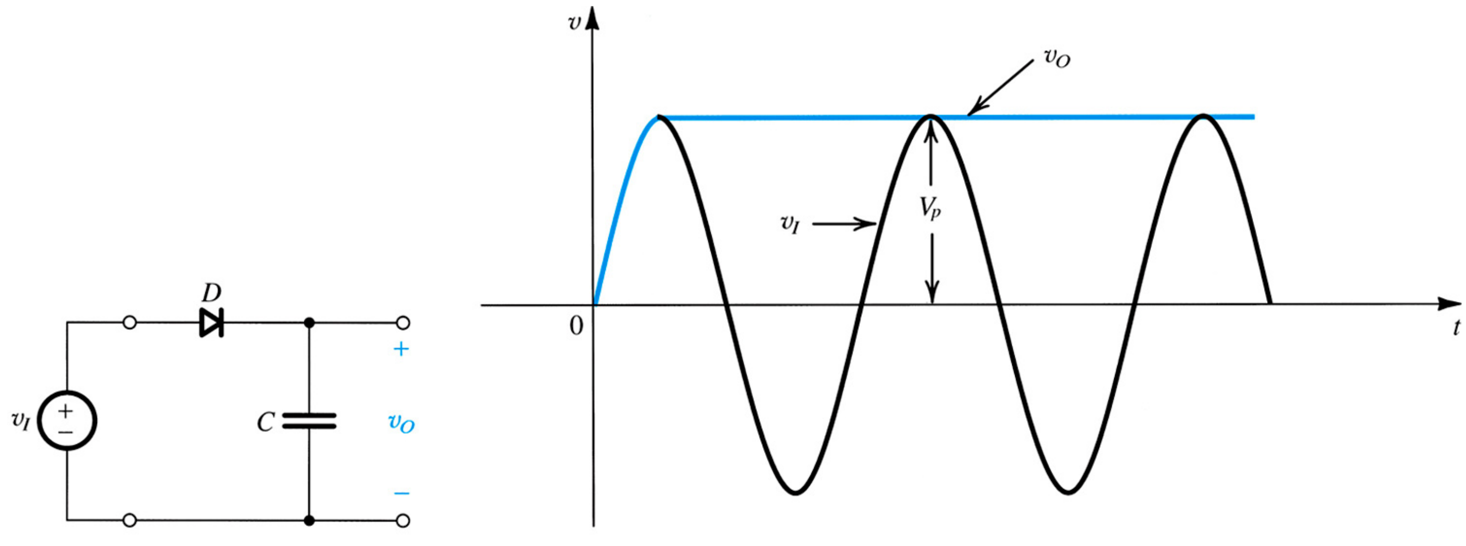


- Diodes can also be used to create **Limiter Circuits** which limit how high and how low a signal can go
  - The gain is set by the rest of the circuit (e.g., an opamp)
- Here a sine wave is limited by diodes to make it look more like a square wave
  - Useful in Phase-Locked Loops (PLLs) and communications circuits

Limiter Circuits



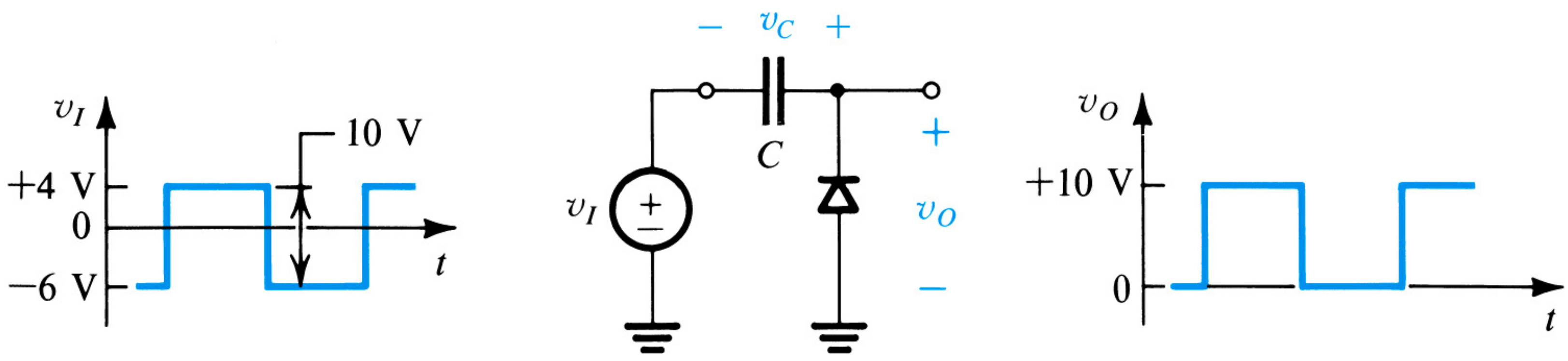
Peak Detector Circuits



(a) (b)

- Diodes are often used to create **Peak Detector** circuits, which output the max (peak) value of an input voltage
  - When V_I goes positive, the diode turns on and charges C to V_P , the peak value of V_I (Ideal diodes assumed here for simplicity)
  - When V_I drops from it's peak value, the diode turns off and C stays charged to V_P until a load or leakage current discharges it
- Useful in communications circuits, power supplies, etc.

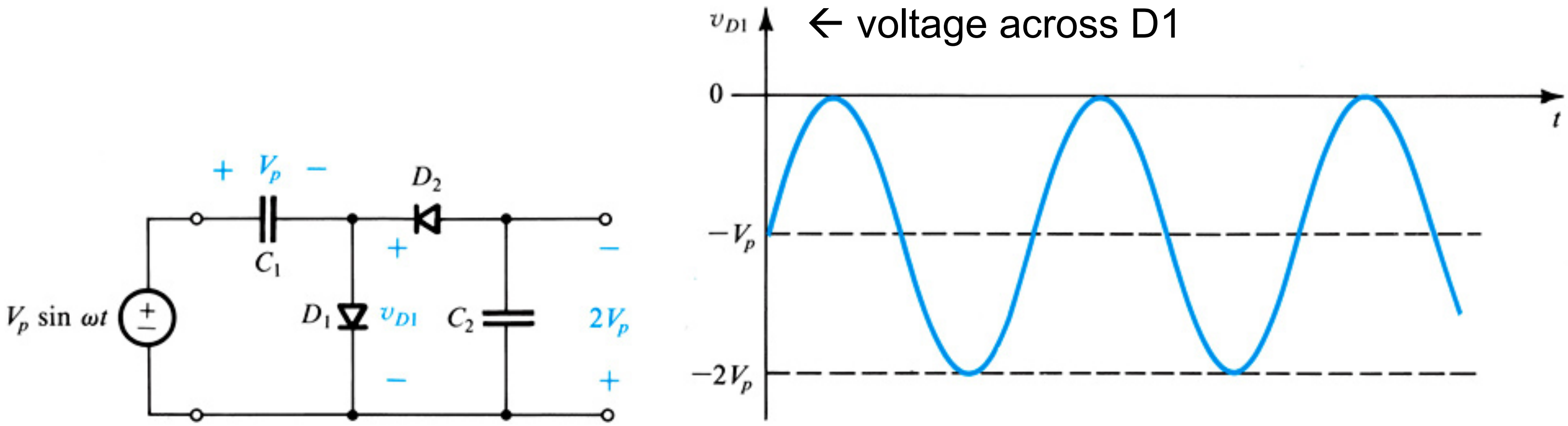
DC Restorer Circuits



(a) (b) (c)

- Also referred to as a **Clamped Capacitor** circuit
- Since the diode turns on and prevents $V_o < 0V$, the capacitor charges up to the peak negative value of V_I
  - In this example, $V_C = +6V$ since the minimum $V_I = -6V$
  - Ideal diodes were assumed here for ease of understanding
- Then when V_I rises the diode turns off and V_o goes up by the total change in voltage in V_I
- Useful in restoring DC values to AC coupled signals, etc.

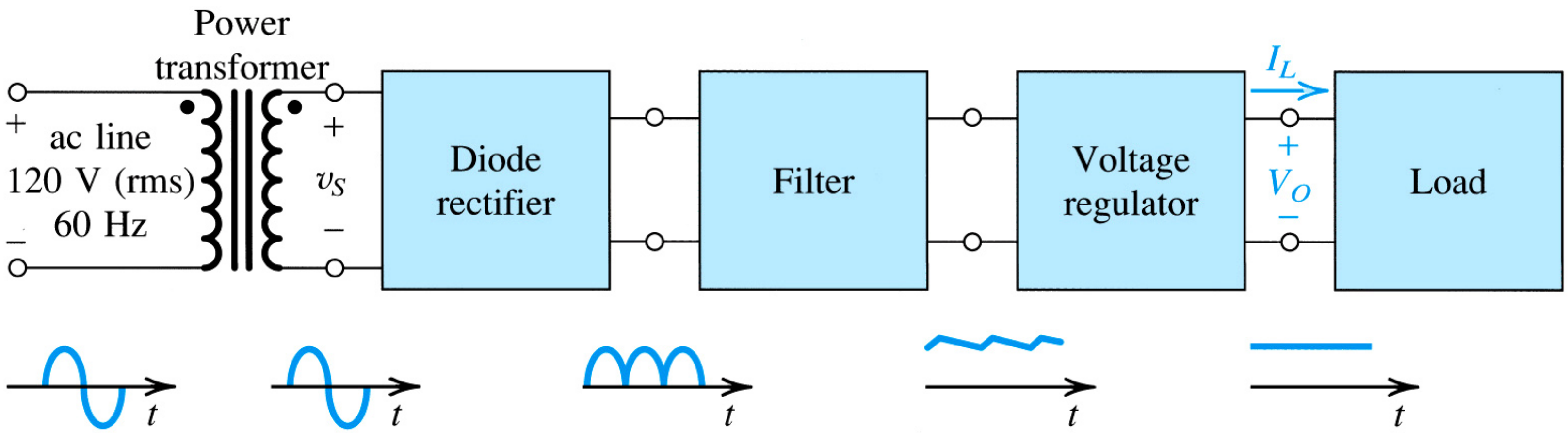
Voltage Doubler Circuits



(a) (b)

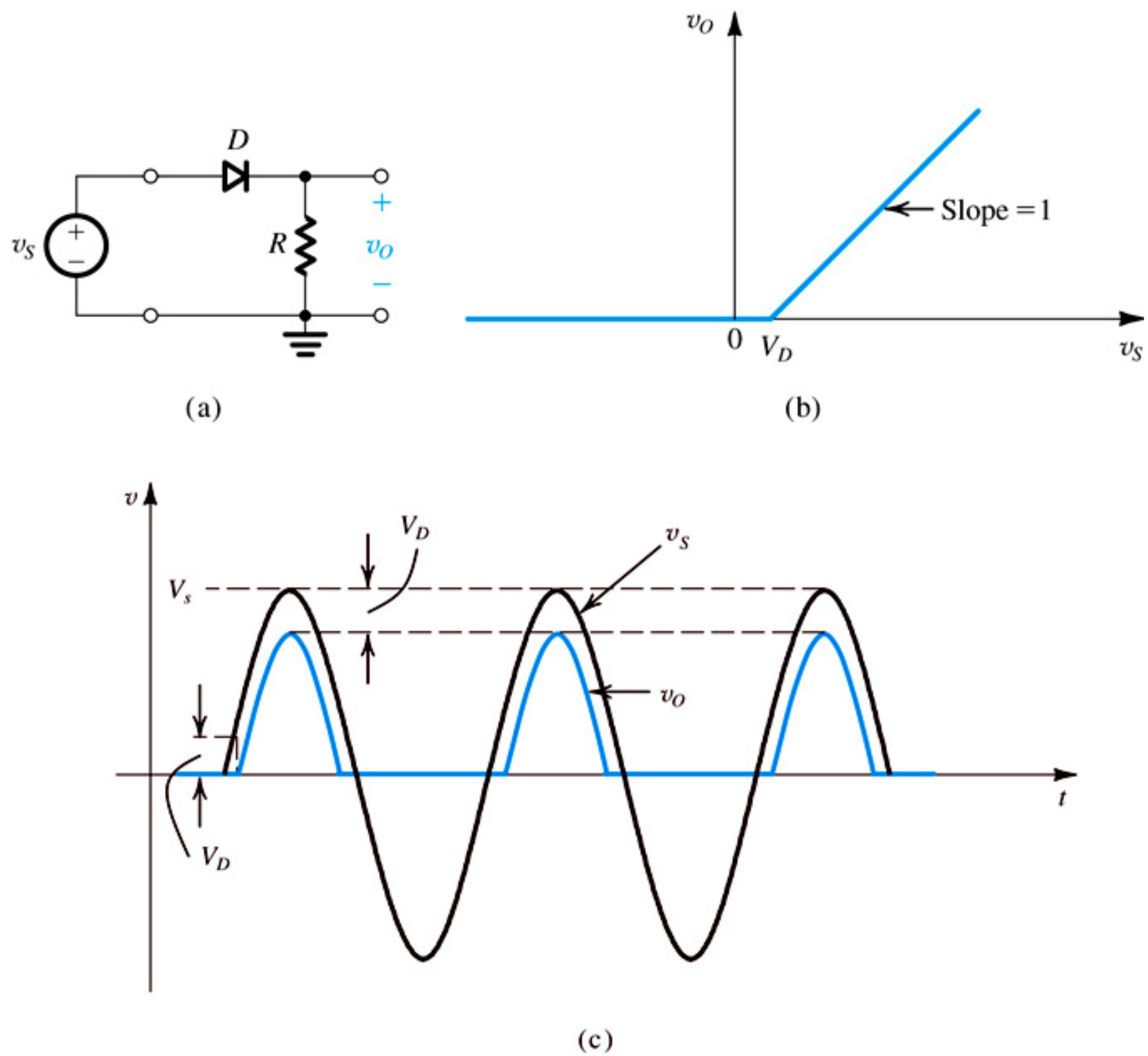
- By combining a clamped capacitor circuit and a peak detector circuit, we can build a **voltage doubler**
  - C_1 and D_1 form the clamped capacitor circuit
  - C_2 and D_2 form the peak detector circuit
- D_1 keeps $V_{D1} < 0V$, so C_1 charges up to $+V_P$
- D_2 turns on to charge C_2 to $-2V_P$ → <u>Vout = 2x the Vin!</u>
- Useful to create voltages > V_{DD} (e.g., for flash memory)

Power Supplies



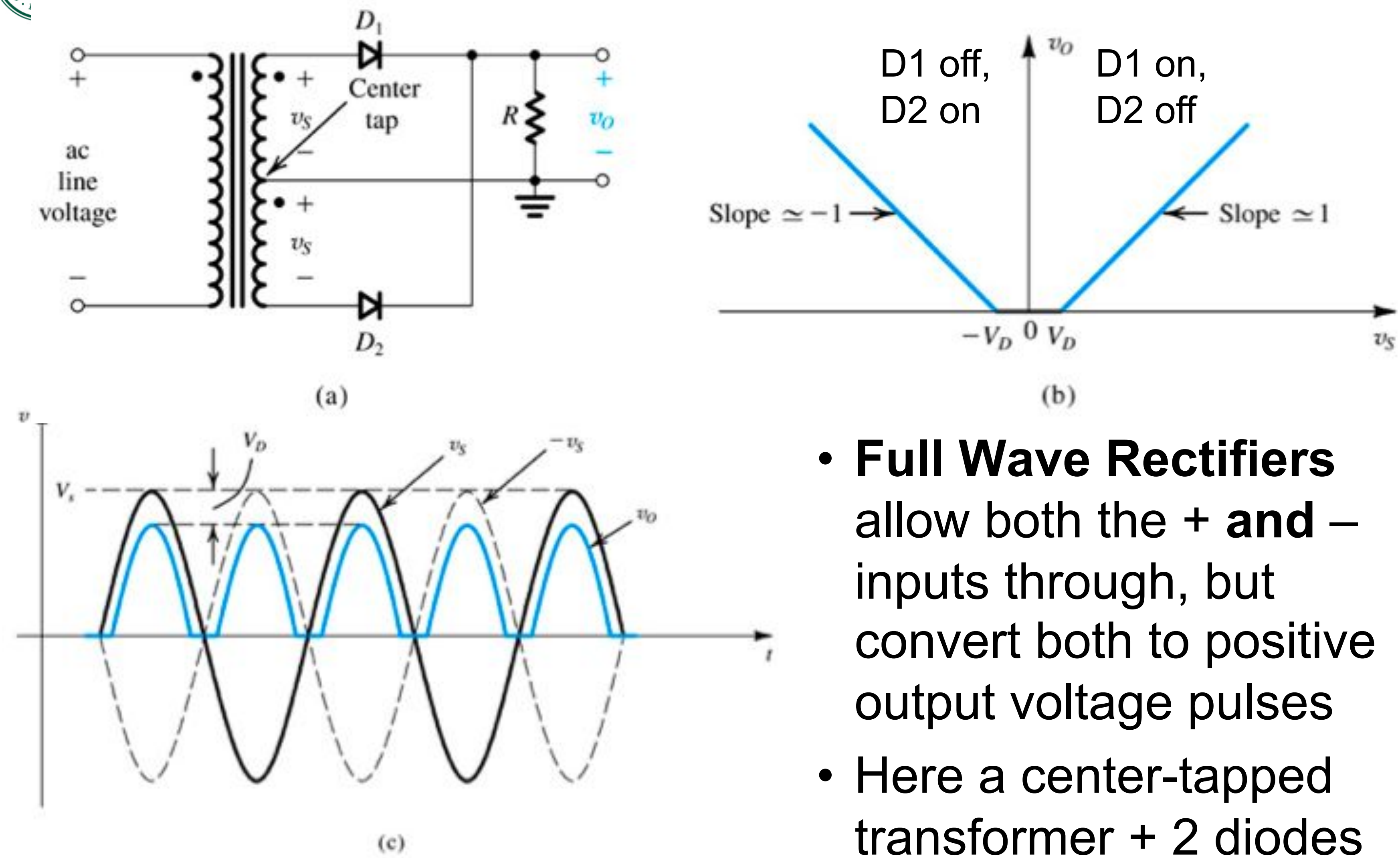
- One of the most useful applications of diodes is for DC Power Supplies, which convert AC Vin into DC Vout
  - A transformer steps down the voltage to a useful value (e.g., 12V), and provides isolation between the user and the AC power grid
  - A diode rectifier converts the bipolar AC voltage into unipolar pulses
  - A filter smoothes out the pulses, leaving only small variations (ripple)
  - A voltage regulator keeps the output voltage constant, as both the input voltage and load current vary (e.g., Zener diode or IC regulator)

Half Wave Rectifiers



- **Half Wave Rectifiers** only allow the + **or** – parts of an input signal through
- Here the diode is on for $V_S > 0.7V$, off for $V_S < 0.7V$
- Some input is lost across the diode
- Diode must handle the **Peak Inverse Voltage (PIV)** (Equal to V_S here)

Full Wave Rectifiers

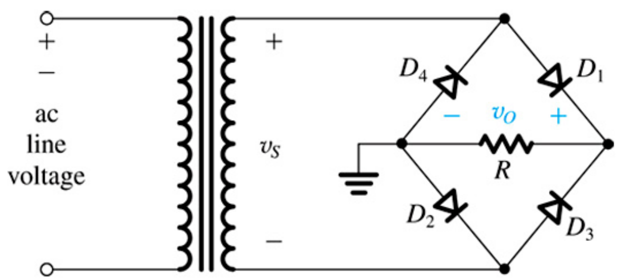


Here the PIV = $2V_S - V_D$

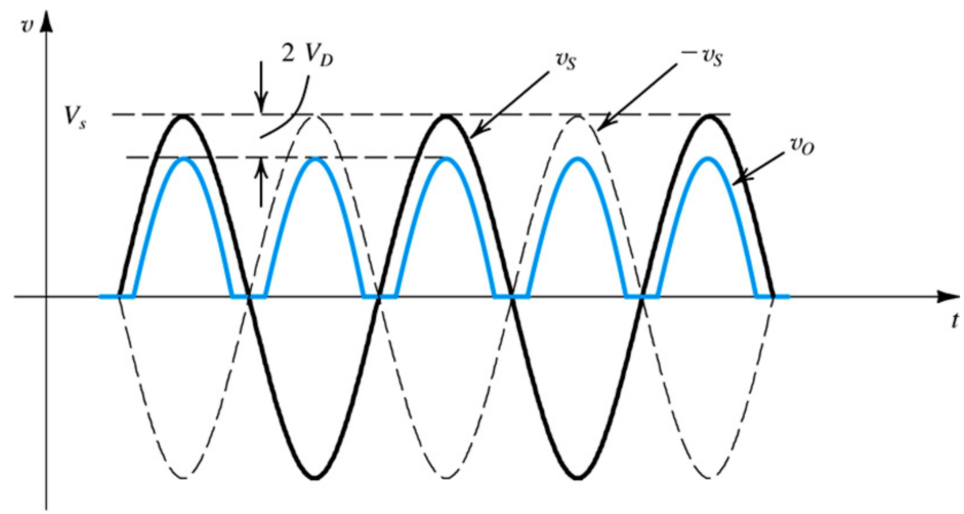
- **Full Wave Rectifiers** allow both the + **and** – inputs through, but convert both to positive output voltage pulses
- Here a center-tapped transformer + 2 diodes are needed for this

Bridge Rectifiers

D1, D2 on and D3, D4 off on + peaks. On - peaks D1, D2 off and D3, D4 on



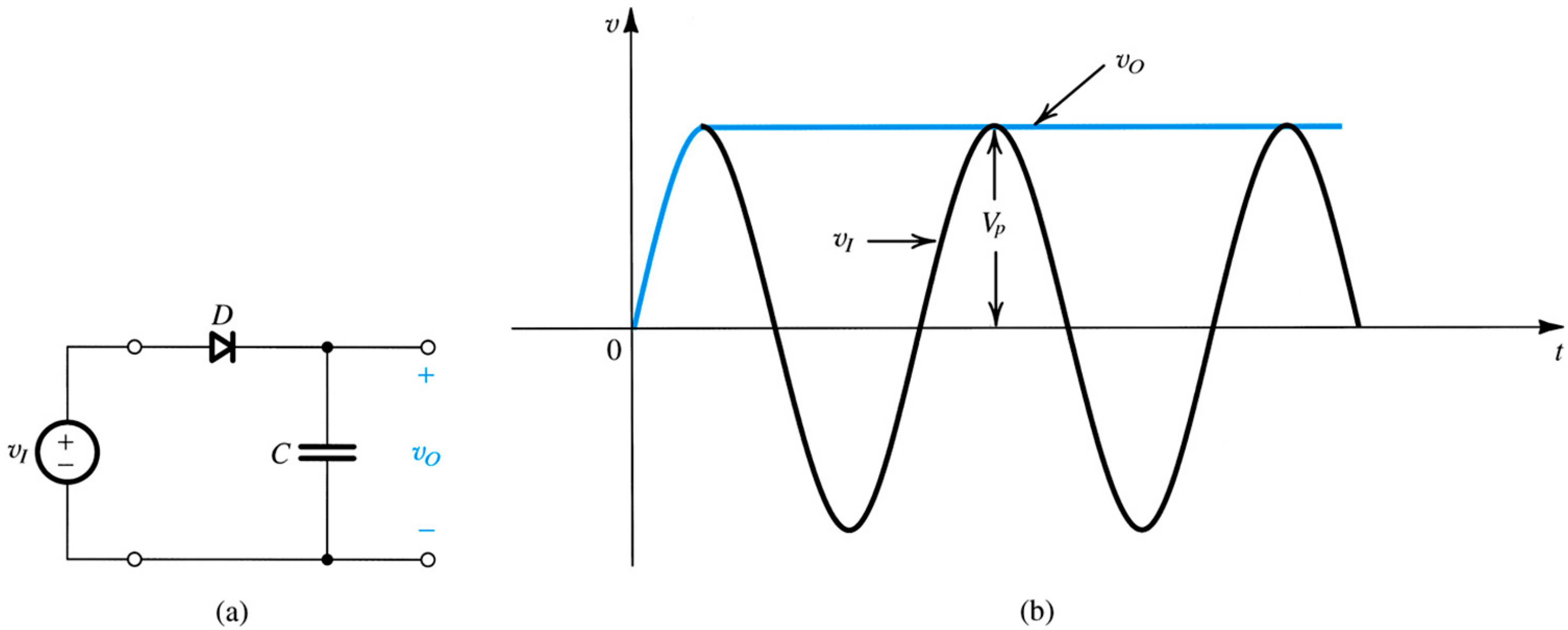
(a)



(b)

- **Bridge Rectifiers** perform full wave rectification without the need for a center-tapped transformer (lower cost)
  – Requires 4 diodes, but these cost less than the transformer
  – Output voltage peaks are slightly lower, at $V_S - 2V_D$
  – Peak Inverse Voltage (PIV) is only $V_S - V_D$, since across 2 diodes
  – Most popular rectifier circuit used for power supplies

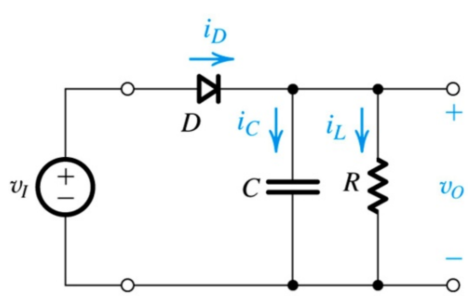
Filter Capacitors



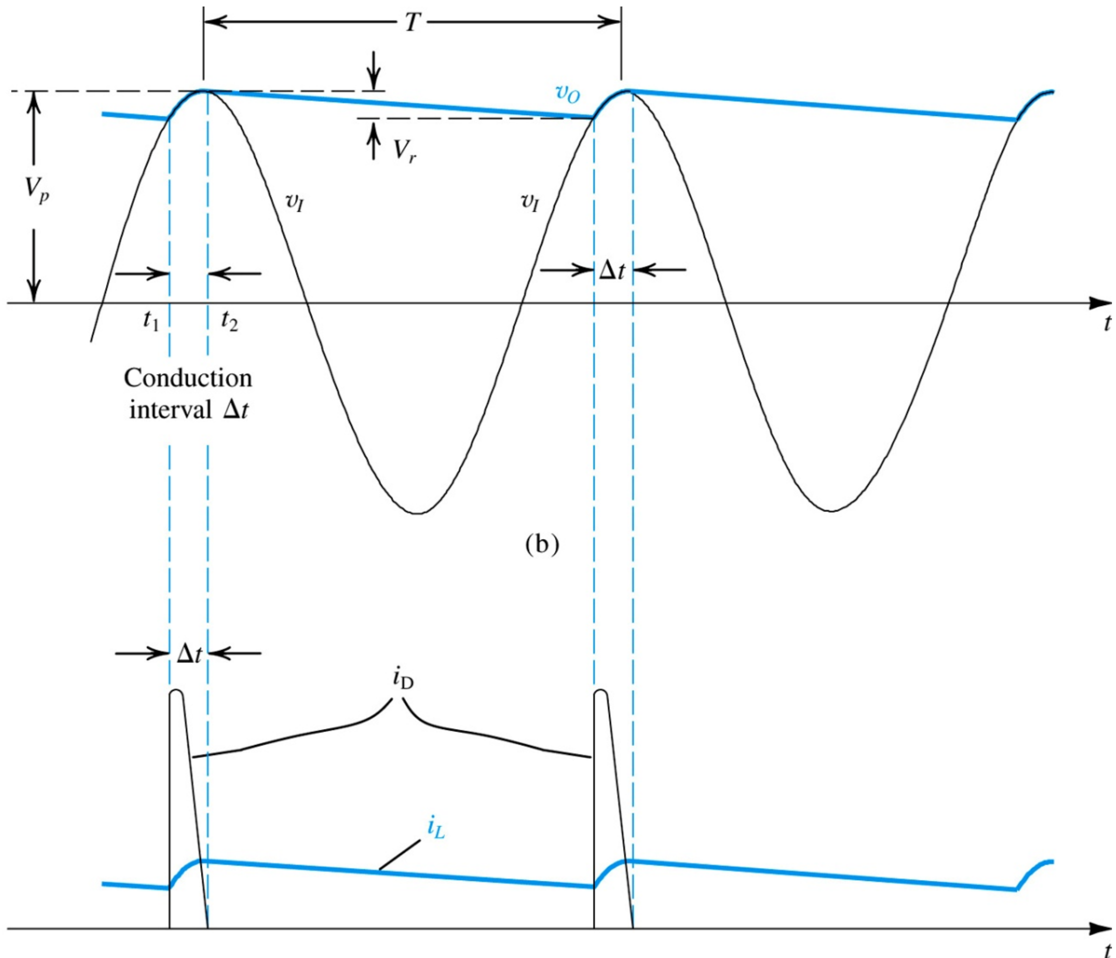
- To filter the pulses from the diode rectifier circuit, a large filter capacitor is used (100-1000μF or larger)
- Larger capacitors reduce ripple more, but also cost more (Shown here without a load current to discharge the cap)

Filter Capacitors

- With a load, the filter capacitor discharges when the diode is off → **Ripple!** (V_r)
- The diode turns on every cycle to replace the lost charge to the cap



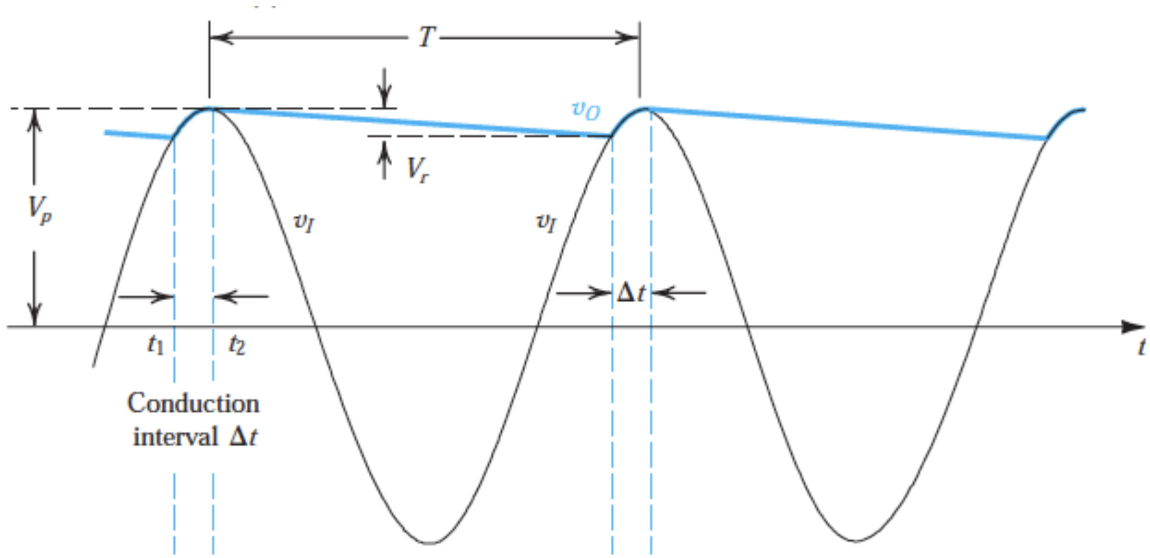
(a)



(b)

(c)

Ripple Voltage



- The filter capacitor is chosen such that RC >> T, so the normal exponential capacitor discharge appears linear

$$I = C\frac{dV}{dt} \approx C\frac{\Delta V}{\Delta t} \quad and \quad I_L \approx \frac{V_P}{R} \quad \Rightarrow \quad \frac{V_P}{R} \approx C\frac{V_r}{T}$$

$$or \quad \boxed{V_r \approx V_P\left(\frac{T}{RC}\right)} \quad which\ can\ also\ be\ written\ as: \quad \boxed{V_r \approx \frac{I_L}{fC}}$$

Average and Peak Diode Current

The charge supplied to the load by the capacitor during T is:

$$I = \frac{\Delta Q}{\Delta t} \Rightarrow \Delta Q = I\,\Delta t \;\Rightarrow\; Q_{lost} = I_L T$$

During Δt the diode must replace this charge lost from the capacitor, plus the load current, I_L :

$$Q_{\sup plied} = Q_{lost} + I_L \Delta\, t = I_L T + I_L \Delta\, t = I_L \left(T + \Delta\, t\right)$$

Therefore the average diode current is given by :

$$I_{Davg} = \frac{Q_{\sup plied}}{\Delta t} = I_L \left(1 + \frac{T}{\Delta t}\right)$$

Average and Peak Diode Current

To find the average diode current, we need to know the **conduction angle ωΔt** and the **conduction interval Δt**

$$V_P - V_r = V_P \cos(\omega\Delta t) \approx V_P\left(1 - \frac{1}{2}(\omega\Delta t)^2\right) \quad \textit{for } \omega\Delta t \textit{ small}$$

$$\Rightarrow \boxed{\omega\Delta t \approx \sqrt{2V_r/V_P}} \quad \textit{and} \quad \boxed{\Delta t \approx \left(\frac{T}{2\pi}\right)\sqrt{\frac{2V_r}{V_P}}}$$

Combining this result with the previous equation for I_{Davg} :

$$\boxed{I_{Davg} = I_L\left(1 + \frac{T}{\Delta t}\right) = I_L\left(1 + \pi\sqrt{\frac{2V_P}{V_r}}\right)}$$

Also, analyzing the differential equation for I_{Dmax} yields :

$$\boxed{I_{D\max} = I_L\left(1 + 2\pi\sqrt{\frac{2V_P}{V_r}}\right) \approx 2I_{Davg}}$$

Example 4.8

Consider a peak rectifier fed by a 60-Hz sinusoid having a peak value $V_p = 100$ V. Let the load resistance $R = 10$ kΩ. Find the value of the capacitance C that will result in a peak-to-peak ripple of 2 V. Also, calculate the fraction of the cycle during which the diode is conducting and the average and peak values of the diode current.

Solution

From Eq. (4.29a) we obtain the value of C as

$$C = \frac{V_p}{V_r fR} = \frac{100}{2 \times 60 \times 10 \times 10^3} = 83.3\ \mu\text{F}$$

The conduction angle $\omega \Delta t$ is found from Eq. (4.30) as

$$\omega \Delta t = \sqrt{2 \times 2/100} = 0.2 \text{ rad}$$

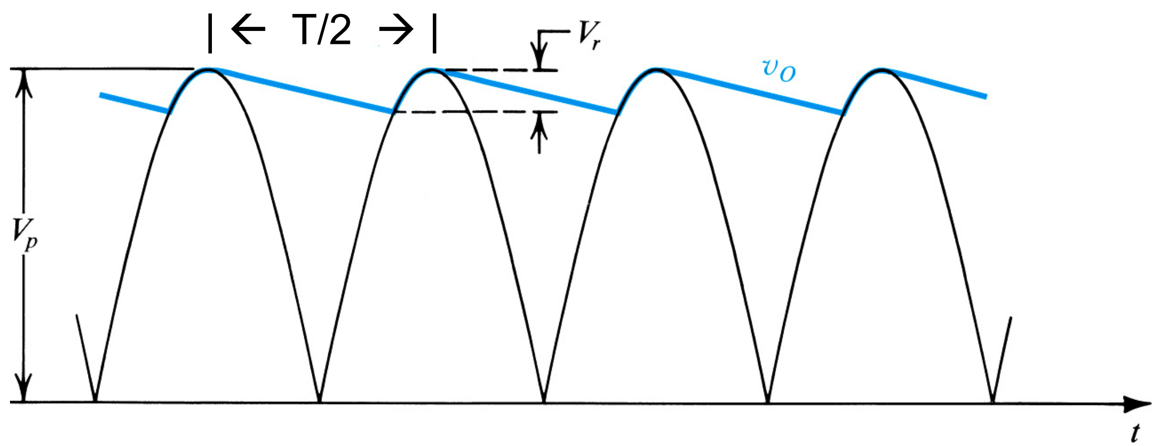
Thus the diode conducts for $(0.2/2\pi) \times 100 = 3.18\%$ of the cycle. The average diode current is obtained from Eq. (4.31), where $I_L = 100/10 = 10$ mA, as

$$i_{Dav} = 10(1 + \pi\sqrt{2 \times 100/2}) = 324 \text{ mA}$$

The peak diode current is found using Eq. (4.32),

$$i_{Dmax} = 10(1 + 2\pi\sqrt{2 \times 100/2}) = 638 \text{ mA}$$

Ripple, I_{Davg}, I_{Dmax} for Full Wave Rectifier



- The equations found for a Half Wave Rectifier can be modified for a Full Wave Rectifier by replacing T with T/2 :

$$\boxed{V_r \approx V_P\left(\frac{T}{2RC}\right) \approx \frac{I_L}{2fC}}$$

$$\boxed{I_{Davg} = I_L\left(1 + \frac{T}{2\Delta t}\right) = I_L\left(1 + \pi\sqrt{\frac{V_P}{2V_r}}\right)}$$

$$\boxed{I_{D\max} = I_L\left(1 + 2\pi\sqrt{\frac{V_P}{2V_r}}\right) \approx 2I_{Davg}}$$

Summary of Key Concepts

- Large-signal models & analysis of forward-biased diodes
  - Exponential, Ideal and Constant Voltage-Drop Diode Models
  - Solving by Iteration, or by Graphical Analysis using Load Lines
- Small-signal analysis & the Small-signal Diode Model
- Models for reverse-biased Zener diodes
- Applications of Diodes
  - Voltage Regulation
  - Diode Logic Circuits
  - Limiting & Clamping Circuits
  - DC Restorer and Voltage Doubler Circuits
- Power Supplies
  - Diode rectifiers, Filters, Voltage regulation