In this case the results are consistent with $D_2$ off.

Thus we conclude that $D_3$ is off and $D_4$ is on.

Exercise 3.5
\[ V_{Lavg} = \frac{V_{L_{\text{max}}} - V_{L_{\text{min}}}}{2} = 15 \text{ V} \]

\[ C = \frac{I_L T}{2V_x} = 0.1(\frac{1}{60}) = 0.4 = 2083 \mu\text{F} \]

\[ V_{L_{\text{max}}} = V_{m, \text{secondary}} - 2V_{\text{diode}} \]

\[ V_{m, \text{secondary}} = 15.2 + 2(0.7) = 16.6 \text{ V} \]

\[ V_{m, \text{primary}} = 110\sqrt{2} = 155.6 \text{ V} \]

\[ n = \frac{V_{m, \text{primary}}}{V_{m, \text{secondary}}} = \frac{155.6}{16.6} = 9.37 \]

**Exercise 3.6**

We determine the capacitance as in Exercise 3.5 resulting in \( C = 2083 \mu\text{F} \). In this case we have \( V_{m, \text{secondary}} = V_{L_{\text{max}}} + V_{\text{diode}} = 15.2 + 0.7 = 15.9 \text{ V} \). Then the required turns ratio is

\[ n = \frac{V_{m, \text{primary}}}{V_{m, \text{secondary}}} = \frac{155.6}{15.9} = 9.78 \]

**Exercise 3.7**

(a)
(c) With the resistor connected to ground as shown, the diodes never conduct and \( v_c = 0 \). Thus we have \( v_o = v_{in} \).

\[ v_{in} = 2 \sin \omega t \]

\[ v_c = -3 \text{V} \]

Exercise 3.10

A solution is shown in Figure 3.21 in the book.

Exercise 3.11

A solution is shown in Figure 3.22 in the book.

Exercise 3.12

We follow the procedure used in Example 3.5 in the book.

For part (a) with \( R_L = 1200 \, \Omega \), we have

\[ V_T = V_{SS} \frac{R_L}{R + R_L} = 24 \frac{1200}{1200 + 1200} = 12 \, \text{V} \]

\[ R_T = \frac{RR_L}{R + R_L} = \frac{1200 \times 1200}{1200 + 1200} = 600 \, \Omega \]
Similarly for part (b) with $R_L = 400 \, \Omega$ we obtain $V_T = 6 \, V$ and $R_T = 300 \, \Omega$. Now we construct the load lines.

At the intersections of the load lines with the diode characteristics we find the answers:

(a) $v_L = -v_D \approx 9.4 \, V$
(b) $v_L = -v_D \approx 6.0 \, V$

**Exercise 3.13**

The load line equation is

$$15 = 100(i_L - i_D) - v_D$$

Substituting the values of $i_L$ for the various parts, we have

(a) $15 = -100i_D - v_D$
(b) $13 = -100i_D - v_D$
(c) $5 = -100i_D - v_D$

We use these equations to plot the load lines as shown on the next page.
At the intersections of the load lines with the diode characteristics we find:

(a) $v_o = -v_D \approx 10 \, \text{V}$
(b) $v_o = -v_D \approx 10 \, \text{V}$
(c) $v_o = -v_D \approx 5 \, \text{V}$

**Exercise 3.14**

Equation 3.21 states: $r_d = \frac{nV_T}{I_{DQ}}$. Furthermore at a temperature of 300 K, we have $V_T \approx 26 \, \text{mV}$. Substituting values and evaluating, we obtain (a) $r_d = 260 \, \Omega$, (b) $r_d = 26 \, \Omega$, (c) $r_d = 2.6 \, \Omega$.

**Exercise 3.15**

(a) First we compute the Q-point diode current. Refer to the dc circuit shown in Figure 3.34 in the book.

$$I_{DQ} = \frac{V_C - 0.6}{R_C} = \frac{1.6 - 0.6}{2 \, \text{k}\Omega} = 0.5 \, \text{mA}$$

Then we can determine the small-signal resistance of the diode:
Problem 3.22

The current through the meter is a half-wave rectified sine wave with a peak amplitude of $(10\sqrt{2})/R$. As shown in Problem 3.21, the average of a half-wave rectified sine wave is its peak value divided by $\pi$. Thus we have

$$\frac{10\sqrt{2}}{R\pi} = 5 \text{ mA}$$

Solving we find $R = 900 \Omega$.

Problem 3.23

Half-wave circuit:

![Half-wave circuit diagram]

Full-wave circuits are shown in Figure 3.13 and 3.14 in the book except that capacitors need to be added in parallel with the loads.

Problem 3.24

![Current waveform diagram]

Peak current flows at the instant for which $v_s(t)$ attains its maximum value. The maximum current is
\[
I_{\text{max}} = \frac{V_m - V_B}{R} = \frac{20 - 14}{10} = 0.6 \text{ A}
\]

As a function of time, the current is

\[
i(t) = \frac{V_m \sin(\omega t) - V_B}{R}
\]

provided that this expression yields a positive result. Otherwise \(i(t) = 0\). To determine the interval for which the diode is in the on state we must solve this equation:

\[
i(t) = 0 = \frac{V_m \sin(\omega t) - V_B}{R} = \frac{20\sin(\omega t) - 14}{10}
\]

Solving we find two roots: \(t_1 = 0.775/\omega\) and \(t_2 = 2.37/\omega\) radian. \(t_1\) and \(t_2\) are indicated on the waveforms shown on the preceding page. The period of the sine wave is \(T = 2\pi/\omega\). Thus the percentage of the time that the diode is on is

\[
diode \text{ on} = \frac{2.37/\omega - 0.775/\omega}{2\pi/\omega} \times 100\% = 25.3\%
\]

**Problem 3.25**

For an average load voltage of 9 V with 2-V peak-to-peak ripple, the maximum load voltage is 10 V and the minimum is 8 V. Because we assume an ideal diode, the peak secondary voltage of the transformer must be 10 V. Thus the turns ratio needed for the transformer is

\[
n = \frac{110\sqrt{2}}{10} = 15.6
\]
Thus placing diodes in parallel does not reduce the dynamic resistance. Dynamic resistance is independent of diode area if the current remains constant.

**Problem 3.57**

The small-signal equivalent circuit for changes in the source voltage is:

\[
\Delta V_{ss} \quad \text{R} \quad r_d \quad r_L \quad \Delta V_{load}
\]

The change in the load voltage is given by

\[
\Delta V_{load} = \Delta V_{ss} \frac{r_d \parallel r_L}{R + r_d \parallel r_L}
\]

Source regulation = \( \frac{\Delta V_{load}}{\Delta V_{ss}} \times 100\% \)

\[
= \frac{r_d \parallel r_L}{R + r_d \parallel r_L} \times 100\%
\]

The small-signal equivalent circuit for changes in the load current is:

\[
\text{R} \quad r_d \quad \Delta V_{load} \quad \text{ΔI}_{load} = \frac{V_{load}}{R_L}
\]

The change in load voltage due to the change in load current is

\[
V_{\text{no-load}} - V_{\text{full-load}} = \Delta V_{load}
\]

\[
= (r_d \parallel r_L) \Delta I_{load}
\]

\[
= (r_d \parallel r_L) \frac{V_{\text{full-load}}}{R_L}
\]
Problem 3.3

A Zener diode is a diode that is intended to be operated in reverse breakdown. It is used as a voltage reference. They are also called breakdown diodes or avalanche diodes (although strictly speaking avalanche diodes and zener diodes are distinct because breakdown is due to different physical mechanisms). A sketch of the volt-ampere characteristic for a 5.6-V Zener diode is:

![Volt-Ampere Characteristic](image)

Problem 3.4

\[ V_D = 0.6 - 2 \times 10^{-3} \times (175 - 25) \]

\[ = 0.3 \text{ V} \]

Problem 3.5

(a)
Problem 3.6

At 70° the reverse diode current is \( i_R = V_o / R = 0.5/10^6 = 500 \text{ nA} \).

At 50° the current is 500 nA/4 = 125 nA and \( V_o = 0.125 \text{ V} \).

At 100° the current is \((500 \text{ nA}) \times 2^3 = 4 \mu\text{A}\) and \( V_o = 4 \text{ V} \).

Problem 3.7

As the diode heats up, its forward voltage decreases by approximately 2 mV/°C. Thus the increase in temperature is \( \Delta T = (0.65 \text{ V} - 0.45 \text{ V})/(2 \text{ mV}) = 100° \). The final diode temperature is \( T_{\text{final}} = T_{\text{start}} + \Delta T = 125°C \).

Problem 3.8

Assuming a forward drop of 0.6 V for each diode, five diodes must be placed in series to obtain a reference voltage of 3 V.
Load regulation = \frac{V_{\text{no-load}} - V_{\text{full-load}}}{V_{\text{full-load}}} \times 100\%

= \frac{(r_d | R_L)}{R_L} \times 100\%

= \frac{r_d}{r_d + R_L} \times 100\%

**Problem 3.58**

(a) \( r_d = \frac{nV_T}{I_{DQ}} = 26 \, \Omega \)

(b) \( \Delta V_D = \Delta i_D r_d = (0.1 \, \text{mA}) \times (26 \, \Omega) = 2.6 \, \text{mV} \)

(c) \( i_D = I_S \left[ \exp \left( \frac{V_D}{nV_T} \right) - 1 \right] \)

\( v_D = nV_T \ln \left( \frac{i_D}{I_S} - 1 \right) \)

For \( i_D = 1 \, \text{mA} \) we find \( v_D = 0.65854 \, \text{V} \) and for \( i_D = 1.1 \, \text{mA} \) we find \( v_D = 0.66102 \, \text{V} \) for a difference of \( \Delta v_D = 2.48 \, \text{mV} \) which is 4.8% lower than the result using the dynamic resistance.

**Problem 3.59**

\( r_d = \left[ \left( \frac{di_D}{dv_D} \right)_Q \right]^{-1} = 1.67 \times 10^6 \times \left( 1 + \frac{V_{DQ}}{5} \right)^4 \)

For \( I_{DQ} = -1 \, \text{mA}, \ V_{DQ} = -4.5 \, \text{V} \) and \( r_d = 167 \, \Omega \)

For \( I_{DQ} = -10 \, \text{mA}, \ V_{DQ} = -4.77 \, \text{V} \) and \( r_d = 7.48 \, \Omega \)
Load regulation = \( \frac{V_{\text{no-load}} - V_{\text{full-load}}}{V_{\text{full-load}}} \times 100\% \)

\[ = \frac{(r_d + R_L)}{R_L} \times 100\% \]

\[ = \frac{r_d}{r_d + R_L} \times 100\% \]

**Problem 3.58**

(a) \( r_d = nV_T/I_{DQ} = 26 \, \Omega \)

(b) \( \Delta V_D = \Delta i_D r_d = (0.1 \, \text{mA}) \times (26 \, \Omega) = 2.6 \, \text{mV} \)

(c) \[ i_D = I_s \left[ \exp \left( \frac{V_D}{nV_T} \right) - 1 \right] \]

\[ v_D = nV_T \ln \left( \frac{i_D}{I_s} - 1 \right) \]

For \( i_D = 1 \, \text{mA} \) we find \( v_D = 0.65854 \, \text{V} \) and for \( i_D = 1.1 \, \text{mA} \) we find \( v_D = 0.66102 \, \text{V} \) for a difference of \( \Delta v_D = 2.48 \, \text{mV} \) which is 4.8% lower than the result using the dynamic resistance.

**Problem 3.59**

\[ r_d = \left( \frac{di_D}{dv_D} \right)^{-1} = 1.67 \times 10^6 \times \left( 1 + \frac{V_{DQ}}{5} \right)^4 \]

For \( I_{DQ} = -1 \, \text{mA} \), \( V_{DQ} = -4.5 \, \text{V} \) and \( r_d = 167 \, \Omega \)

For \( I_{DQ} = -10 \, \text{mA} \), \( V_{DQ} = -4.77 \, \text{V} \) and \( r_d = 7.48 \, \Omega \)

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Problem 3.60

\[ I_L = \frac{V_L}{R_L} = \frac{5}{100} = 50 \text{ mA} \]

\[ I_{\text{source}} = \frac{(8 - 5)}{20} = 150 \text{ mA} \]

\[ I_{\text{QZenner}} = I_{\text{source}} - I_L = 100 \text{ mA} \]

Small-signal equivalent circuit:

Let \( R'_L = R_L || r_d \), then we can write:
\[ V_{\text{ripple, out}} = 10 \text{ mV} = (1 \text{ V}) \times \frac{R_L'}{R_L' + R} \]

Solving we find \( R_L' = 0.202 \Omega \). Thus we have \( R_L' = 0.202 = \frac{1}{1/r_d + 1/R_L} \) which yields \( r_d = 0.202 \Omega \).

**Problem 3.61**

See Figures 3.36 and 3.37 in the book.

**Problem 3.62**

In an intrinsic semiconductor, the free electron and hole concentrations are equal.

**Problem 3.63**

Free electrons and holes are generated by thermal energy that causes covalent bonds to break. The higher the temperature, the higher the rate of generation. When a free electron encounters a hole, recombination can occur in which the hole and free electron combine to form a filled covalent bond. As the concentration of holes and electrons builds up, recombination occurs more frequently. At a given temperature, an equilibrium exists for which the rate of recombination equals the rate of generation of charge carriers. As temperature increases, this equilibrium occurs for larger concentrations of charge carriers.

**Problem 3.64**

The conductivity of intrinsic silicon increases with temperature because the free-electron and hole concentrations increase with temperature.

**Problem 3.65**

See Figures 3.39 and 3.40 in the book.

**Problem 3.66**

\[ p + N_D = n + N_A \]