Chapter 9 Instructor Notes

After a brief introduction to semiconductors materials in Section 9.1, Section 9.2 introduces the *pn* junction and the semiconductor diode equation and *i-v* curves. These sections could be bypassed in favor of a more intuitive presentation, provided in Section 9.3 with an explanation of the basic circuit behavior of the diode, beginning with large-signal models. This explanation is supplemented by the sidebar *Make the Connection: Hydraulic Check Valves* (pp. 466-467), which continues the electric-hydraulic analogy introduced in earlier chapters, and provides an intuitive explanation of the operation of the semiconductor diodes[1.] The box *Focus on Methodology: Determining the Conduction State of a Diode* (p. 467) helps the student understand how diode state of conduction can be determined. The large-signal circuit model material is probably sufficient for the purposes of most introductory courses.

5nstructors who are interested in introducing the subject of small-signal models, in preparation for a the study of transistor small-signal amplifiers, may find the rest of the section, covering small-signal diode models (pp. 474-483), of interest. The concept of operating point is introduced, with a review of the load-line equation and the definition of the quiescent operating point of a device. The box *Focus on Methodology: Determining the Operating Point of a Diode* (p. 475) summarizes this material. Section 3.8 can be recalled (or introduced for the first time) at this point. The solution methods used in Examples 9.5, 9.6, 9.7 emphasize the use of simple circuit models for the diode, together with the use of Thèvenin equivalent circuits; this method is quite general, and will reinforce the importance (and understanding) of the concept of equivalent circuits in analyzing more advanced circuits.

The use of Device Data Sheets is continued in this chapter with a summary data sheet on a general purpose diode. The box *Focus on Methodology: Using device data sheets* (pp. 476-477) is designed to familiarize the student with the basic contents and function of device data sheets. The instructor may wish to expand on this introductory presentation by asking students to locate data sheets in the accompanying CD-ROM or on the web, and to identify specific devices and their parameters for use in homework problems.

Section 9.4 discusses various diode rectifier circuits; Section 9.5 introduces DC power supplies; Zener diode circuits and voltage regulation. Section 9.6 analyzes various signal processing circuits, and introduces two application examples in the boxes *Focus on Measurements: Peak Detector Circuit for Capacitive Displacement Transducer* (pp. 499-501), which is tied to two earlier boxeson the capacitive displacement transducer (pp. 147-148 and pp. 175-177), and *Focus on Measurements: Diode Thermometer* (pp. 502-503). The latter example can be tied to a laboratory experiment[2.] Finally, Section 9.7 introduces photodiodes and solar cells and includes the box *Focus on Measurements: Opto-Isolators* (p. 506)

The homework problems present a graded variety of problems, mostly related to the 17 examples and application examples presented in the text.

Learning Objectives

1. Understand the basic principles underlying the physics of semiconductor devices in general, and of the *pn* junction in particular. Become familiar with the diode equation and *i-v* characteristic. Sections 1, 2.
2. Use various circuit models of the semiconductor diode in simple circuits. These are divided into two classes: large signal model, useful to study rectifier circuits, and small signal models, useful in signal processing applications. Section 2.
3. Study practical full-wave rectifier circuits and learn to analyze and determine the practical specifications of a rectifier using large-signal diode models. Section 3.
4. Understand the basic operation of Zener diodes as voltage references, and use simple circuit models to analyze elementary voltage regulators. Section 4.
5. Use the diode models presented in Section 2 to analyze the operation of various practical diode circuits in signal processing applications. Section 5.
6. Understand the basic principle of operation of photodiodes, including solar cells, photosensors and light-emitting diodes. Section 6.

---

[1] With many thanks to Bill Ribbens, who first suggested this idea to me some 20 years ago.

[2] G. Rizzoni, A Practical Introduction to Electronic Instrumentation, 3rd Edition, Kendall-Hunt, 1998.

Section 9.1: Electrical Conduction in Semiconductor Devices

Section 9.2: The pn Junction and the Semiconductor Diode

Problem 9.1

Solution:

Known quantities:
The Ionized Acceptor Density for a doped Silicon:

$$N_a = N_a^- = 10^{17}\ \frac{1}{\text{m}^3},\ N_d = 0$$

Find:
a) If this material is an N or P type extrinsic semiconductor.
b) Which are the majority and which the minority charge carriers.
c) The density of majority and minority carriers.

Analysis:

a) Each acceptor dopant atom introduces an additional positive charge carrier and a negative atomic ion. The ion is NOT a charge carrier. The density of positive carriers [holes] increases because of the doping so the material is extrinsic P type Silicon.

b) The majority carriers are the positive carriers or valence band holes; the minority carriers are the negative carriers or conduction band free electrons.

c) $$CNE:\ p_{po} + 0 - n_{po} - N_a^- = 0, \qquad CPE:\ n_{po} = \frac{n_{io}^2}{p_{po}}$$

$$p_{po} - \frac{n_{io}^2}{p_{po}} - N_a^- = 0, \qquad p_{po}^2 + p_{po}\left(-N_a^-\right) + \left(-n_{io}^2\right) = 0$$

Using the quadratic equation:

$$p_{po} = -\frac{1}{2}\left(-N_a^-\right) \pm \frac{1}{2}\left(\left(-N_a^-\right)^2 - 4\left(-n_{io}^2\right)\right)^{1/2} = -\frac{1}{2}\left(-10^{17}\right) \pm \frac{1}{2}\left(\left(-10^{17}\right)^2 - 4\left(-2.2510^{32}\right)\right)^{1/2} =$$

$$= 510^{16} \pm 5.2210^{16} = 1.02210^{17}\ \frac{1}{\text{m}^3}$$

where the negative answer is physically impossible.
Now use the CPE to obtain the minority carrier density:

$$n_{po} = \frac{n_{io}^2}{p_{po}} = \frac{2.2510^{32}}{1.02210^{17}} = 2.20210^{15}\ \frac{1}{\text{m}^3}$$

Note that because of the doping, the hole density is now about 100 times the electron density. The thermally produced carriers present in the intrinsic Silicon before doping has a small effect on the carrier densities in the extrinsic Silicon. At higher doping levels, the effect becomes negligible.
As temperature increases, the densities of the thermally produced carriers increase and their effect on the final carrier densities increase. At very high temperatures [about 175 C for Silicon] the thermally produced carriers primarily determine the final carrier densities and the doping has a negligible effect [ie, the semiconductor behaves as an intrinsic material]. This is why semiconductors cannot operate in high temperature environments.

Problem 9.2

Solution:

Known quantities:
The intrinsic Silicon is doped:

$$N_a = N_a^- = 10^{17} \frac{1}{\text{m}^3},\ N_d = N_d^+ = 510^{18} \frac{1}{\text{m}^3}$$

Find:
a) If the silicon is an N or P type extrinsic semiconductor.
b) Which are the majority and which the minority charge carriers.
c) The density of majority and minority carriers.

Analysis:
a) N Type
b) Majority = Conduction band free electrons = Negative carriers.
Minority = Valence band holes = Positive carriers.

c) $n_{no} \approx 4.910^{18} \frac{1}{\text{m}^3}$, $p_{no} = 4.5910^{13} \frac{1}{\text{m}^3}$

Problem 9.3

Solution:

Find:
Describe the microscopic structure of semiconductor materials. What are the three most commonly used semiconductor materials?

Analysis:

Semiconductor materials are crystalline with the atoms arranged in a repeated three dimensional array. The distance between atoms in the array is the "lattice constant".
Each atom of a semiconductor has four valence electrons. These electrons participate in covalent bonds with the valance electrons of other atoms.
For certain materials with the properties above, quantum/wave mechanics predicts that the valance electrons may have a total energy [kinetic plus Coulombic potential energy] within certain "allowed" bands. The two most important bands are the valence band containing the valence electrons in covalent bonds and the conduction band containing conduction or free electrons which have obtained enough energy to escape from its covalent bond.
Separating these two allowed bands is the "energy gap" extending over those energies which the electrons are "forbidden" to have.
For semiconductor materials, the energy gap is on the order of 1 electron-Volt [eV].
Silicon is the most common semiconductor material and is used in a variety of applications and devices.
Germanium is used in some optical devices and other special purpose devices.
Gallium Arsenide is a compound III-V semiconductor material. One atom has three and the other has five valence electrons giving an average of four per atom. It is used in microwave, optical, and very high speed digital devices.

Problem 9.4

Solution:

Find:
Describe the thermal production of charge carriers in a semiconductor and how this process limits the operation of a semiconductor device.

Analysis:

At a temperature of absolute zero, ALL valence electrons in a semiconductor are contained in a covalent bond and there are NO charge carriers.
The internal or thermal energy of a solid material is caused by the vibration of the atoms and electrons about their equilibrium position. As the temperature of the material increases, its thermal vibrational energy increases. Some electrons will gain sufficient energy to escape the covalent bond in the valence band, and "jump" past the energy gap into the conduction band. As a consequence, TWO charge carriers are generated. The conduction or free electron in the conduction band is a negative charge carrier. The vacancy in the valence band covalent bond or "hole" is a positive charge carrier.
A conduction band electron may also give up energy and recombine with a valence band hole.
The generation and recombination rates both increase with temperature. At any particular temperature, they are equal and produce equal equilibrium densities of electrons and holes. The equilibrium carrier densities increase with temperature. For Silicon at T = 300 K [approximately room temperature]:

$$n_{io} = p_{io} = 1.510^{10}\ \frac{\text{carriers}}{\text{cm}^3} = 1.510^{16}\ \frac{\text{carriers}}{\text{m}^3}$$

[A number of carriers is a dimensionless quantity and may be omitted from the units.]
Almost all semiconductors devices are "doped" to achieve DIFFERENT densities of positive and negative carriers. A "P-type" semiconductor has a higher density of positive carriers and an "N-type" semiconductor has a higher density of negative carriers. However, at high temperatures the density of thermally produced carriers becomes very large and significantly reduces or nullifies the effects of the doping, ie, the positive and negative carrier densities become nearly equal. For this reason, semiconductor devices cannot be used in high temperature applications. The limit in temperature depends on the semiconductor material.

Problem 9.5

Solution:

Find:

Describe the properties of donor and acceptor dopant atoms and how they affect the densities of charge carriers in a semiconductor material.

Analysis:

An "intrinsic" semiconductor material is undoped. When dopant atoms are added the material becomes an "extrinsic" semiconductor. Doping results in the replacement of an intrinsic atom with a dopant atom. As few as one out of every million intrinsic atoms may be replaced.
A "donor" dopant atom has 5 valence electrons. Only 4 are required to complete the bonding structure in the semiconductor material. The 5th electron requires very little energy to escape to the conduction band and become a negative charge carrier. This leaves behind a donor atom with one missing electron or a negative atomic ion. The ion is immobile and cannot move through the material; therefore, IT IS NOT A CHARGE CARRIER.
Each donor contributes an additional negative carrier to the material. The increased density of negative carriers results in an increased recombination rate which reduces the density of positive carriers. [The PRODUCT of the two densities remains constant.] Materials doped with donor atoms are N type extrinsic semiconductors. The majority carriers are conduction band electrons, the minority carriers are valence band holes.
An "acceptor" dopant atom has 3 valence electrons; however, 4 are required to complete the bonding structure in the semiconductor material. The "missing" 4th electron causes a vacancy or hole in the bonding structure. Another valence electron may move to and occupy this hole thus eliminating it and generating another hole and a negative atomic ion. The ion is immobile and cannot move through the material; therefore, IT IS NOT A CHARGE CARRIER.
Each acceptor contributes an additional positive carrier to the material. The increased density of positive carriers results in an increased recombination rate which reduces the density of negative carriers. [The PRODUCT of the two densities remains constant.] Materials doped with acceptor atoms are P type

extrinsic semiconductors. The majority carriers are valance band holes, the minority carriers are conduction band electrons.

Problem 9.6

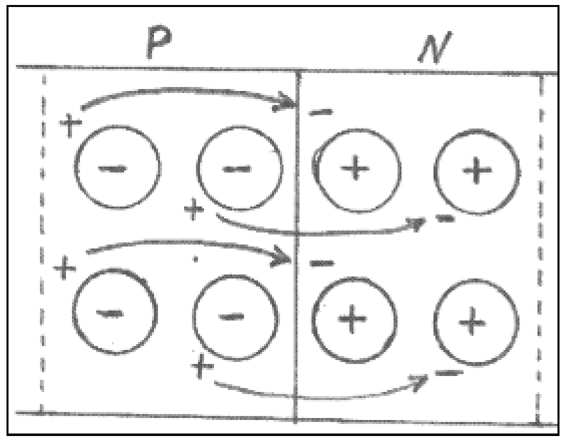
Solution:

Find:

Physically describe the behavior of the charge carriers and ionized dopant atoms in the vicinity of a semiconductor PN junction that causes the potential [energy] barrier that tends to prevent charge carriers from crossing the junction.

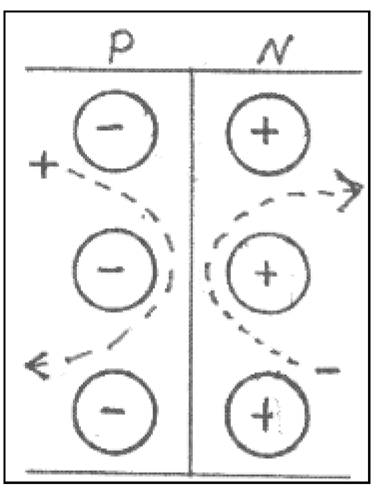
Analysis:

Semiconductor atoms are not shown in the two figures. The circles represent ionized dopant atoms and the uncircled plus and minus signs represent charge carriers. The dotted line in the first figure represents how far the depletion/space charge region extends into the P and N regions.



Near the junction, the negative carriers in the N material recombine with the positive carriers in the P material. This forms a small region on either side of the junction which is depleted of charge carriers; however, the ionized dopant atoms are immobile and remain. Therefore, in the N material the region has a net positive charge and in the P material the region has a net negative charge. This region is called either a "depletion" region [depleted of carriers] or a "space charge" region [due to the dopant ions].

If a conduction band free electron [a majority carrier] in the N material tries to cross into the P material, it encounters and is repelled by the net negative charge [due to the ionized acceptor atoms] in the depleted part of the P material.



If a valence band hole [a majority carrier] in the P material tries to cross into the the N material, it encounters and is repelled by the net positive charge [due to the ionized donor atoms] in the depleted part of the N material.

The repulsion of the carriers is characterized as a Coulombic "potential [energy] barrier". With no voltage applied across the junction, Ohm's law requires the current to be zero. Actually, very, very small equal but opposite currents do flow across the junction but the net curent is zero.

The barrier can be decreased by applying a "forward bias" voltage across the junction. This allows more carriers to cross the junction and when this voltage is greater than a certain value [0.7 V for Silicon] a significant current [milliamps] flows.

The barrier can be increased by applying a "reverse bias" voltage across the junction. This increases the barrier and fewer majority carriers have sufficient energy to cross the junction, ie, the current essentially ceases. However, there is a VERY, VERY small "reverse saturation current" [in the femtoamps range] due to the minority carriers. Since the minority carriers are thermally produced, this current is dependent on temperature.

Section 9.3: Circuit Models for the Semiconductor Diode

Focus on Methodology: Determining the conduction state of an ideal diode

1. Assume a diode conduction state (on or off).
2. Substitute the ideal diode circuit model into the circuit (short circuit if "on", open circuit if "off").
3. Solve for diode current and voltage using linear circuit analysis techniques.
4. If the solution is consistent with the assumption, then the initial assumption was correct; if not, the diode conduction state is opposite to that initially assumed. For example, if the diode has been assumed "off", but the diode voltage computed after replacing the diode with an open circuit is a forward bias, then it must be true that the actual state of the diode is "on".

Focus on Methodology: Determining the operating point of a diode

1. Reduce the circuit to a Thévenin or Norton equivalent circuit, with the diode as the load.
2. Write the load line equation, 9.15.
3. Solve numerically two simultaneous equations in two unknowns (the load-line equation and the diode equation) for the diode current and voltage.

or

4. Solve graphically by finding the intersection of the diode curve (e.g., from a a data sheet) with the loadline. The intersection of the two curves is the diode operating point.

Problem 9.7

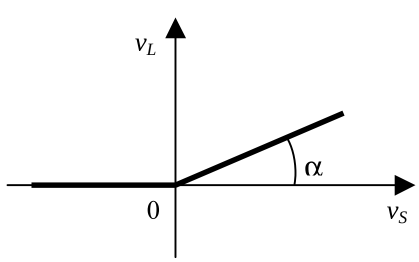
Solution:

Known quantities:
The circuit of Figure P9.7.

Find:
A plot of v_L versus v_S.

Analysis:
For $v_S < 0$, the diode is reverse biased, and $v_L = 0$. For $v_S \geq 0$, the diode is forward biased, and

$$v_L = v_S\left(\frac{R_L \| R_1}{R_S + R_L \| R_1}\right).$$



Where $\alpha = \tan^{-1}\left(\frac{R_L \| R_1}{R_S + R_L \| R_1}\right)$

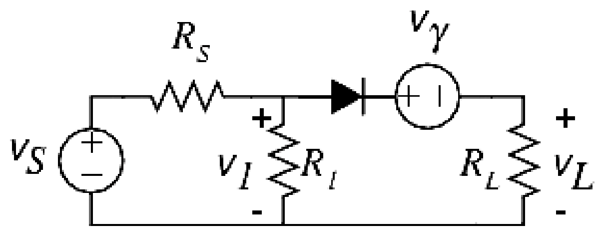
Problem 9.8

Solution:

Known quantities:
The circuit of Figure P9.7 using the offset diode model.

Find:
A plot of v_L versus v_S.

Analysis:
The circuit can be represented as shown in the following figure.



For $v_1 < V_\gamma$, the diode is reverse biased, and $v_L = 0$.

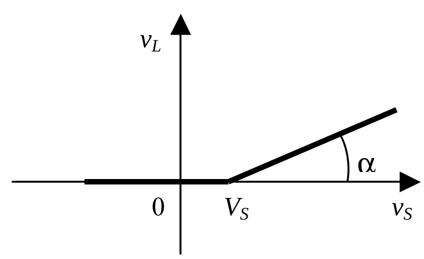
In term of v_S, we have

$$v_L = 0 \Leftrightarrow v_S < V_\gamma\left(1+\frac{R_S}{R_1}\right)$$

For $v_1 \geq V_\gamma$, i.e. $v_S \geq V_\gamma\left(1+\frac{R_S}{R_1}\right)$ the diode is forward biased, and

$$v_1 = \frac{\frac{v_S}{R_S}+\frac{V_\gamma}{R_L}}{\frac{1}{R_S}+\frac{1}{R_1}+\frac{1}{R_L}}.$$

$$v_L = v_1 - V_\gamma = \frac{\frac{v_S}{R_S}-V_\gamma\left(\frac{1}{R_S}+\frac{1}{R_1}\right)}{\frac{1}{R_S}+\frac{1}{R_1}+\frac{1}{R_L}}$$



Where $V_S = V_\gamma\left(1+\frac{R_S}{R_1}\right), \alpha = \tan^{-1}\left(\frac{\frac{1}{R_S}}{\frac{1}{R_S}+\frac{1}{R_1}+\frac{1}{R_L}}\right).$

Problem 9.9

Solution:

Known quantities:
For the circuit of Figure P9.7: $v_S = 6\text{ V}$, and the resistances $R_1 = R_S = R_L = 1\text{k}\Omega$.

Find:
Determine i_D and v_D graphically.

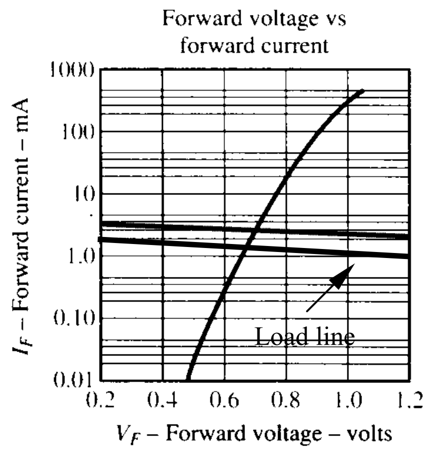
Assumptions:
Use the diode characteristic of the 1N461A.

Analysis:

Replace the diode with an open circuit, and $v_{D_{OC}} = 3 \text{ V}$.

Replace the diode with a short circuit, and $i_{D_{SC}} = \frac{1}{2}\frac{6}{1500} = 2 \text{ mA}$

These are the end points of the load line.
The load line is superimposed on the diode characteristic in the figure.



From the intersection of the load line and the diode characteristic, we see that $i_D \approx 1.5$ mA and $v_D \approx 0.75$ V.

Problem 9.10

Solution:

Known quantities:
The current $I = 1 \text{ mA}$, that make the diode to be above the knee of its $i - v$ characteristic.

Find:

a) The value of R to establish a 5 mA current in the circuit.
b) With the value of R established in the preceding part, what is the minimum value to which the voltage E could be reduced and still maintain diode current above the knee.

Assumptions:
$V_\gamma = 0.7 \text{ V}$.

Analysis:

a)

$$R = \frac{5 - 0.7}{5\ 10^{-3}} = 860\ \Omega$$

b)

$$I = \frac{E_{min} - 0.7}{860} = 1\ 10^{-3}$$

$$\Rightarrow E_{min} = 0.86 + 0.7 = 1.56 \text{ V}$$

Problem 9.11

Solution:

Known quantities:
The circuit of Figure P9.11 driven by a sinusoidal source of $50 \text{ V } rms$, $V_\gamma = 0.7 \text{ V}$, $R = 220\,\Omega$.

Find:

a) The maximum forward current.

b) The peak inverse voltage across the diode.

Analysis:

a) $I_{F_{max}} = \dfrac{50\sqrt{2} - 0.7}{220} = 318 \text{ mA}$

b) $V_{rev_{max}} = 50\sqrt{2} = 70.7 \text{ V}$

Problem 9.12

Solution:

Known quantities:
The configurations shown if Figure P9.12.

Find:
Which diode are forward biased, and which are reverse biased.

Analysis:
a) reverse-biased
b) forward-biased
c) reverse-biased
d) forward-biased
e) forward-biased

Problem 9.13

Solution:

Known quantities:
The configuration shown if Figure P9.13.

Find:
The range of V_{in} for which D_1 is forward-biased.

Analysis:
The diode D_1 is clearly forward-biased for any $V_{in} > 0$.

Problem 9.14

Solution:

Known quantities:
The configurations of Figure P9.14.

Find:
Determine which diodes are forward-biased and which are reverse-biased. Determine the output voltage.

Assumptions:
The drop across each forward biased diode is 0.7 V.

Analysis:

a) D_2 and D_4 are forward biased; D_1 and D_3 are reverse biased. $v_{out} = -5 + 0.7 = -4.3 \text{ V}$

b) D_1 and D_2 are reverse biased; D_3 is forward biased. $v_{out} = -10 + 0.7 = -9.3 \text{ V}$

c) D_1 is reverse biased; D_2 is reverse biased.

Problem 9.15

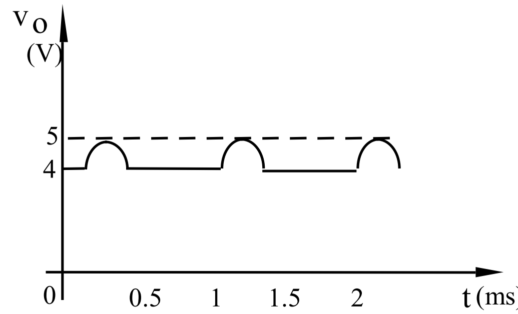
Solution:

Known quantities:
The circuit of Figure P9.15; $v_S(t) = 10\,sin(2{,}000\pi t)$.

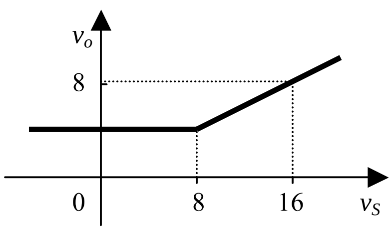
Find:
The output waveform and the voltage transfer characteristic.

Assumptions:
The diode is ideal.

Analysis:



For v_S <8 V, v_o=4 V. For $v_S \geq$ 8 V, v_o= v_S /2.
The voltage transfer characteristic is



Problem 9.16

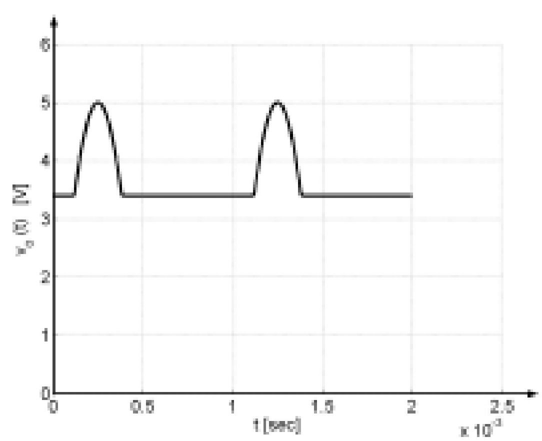
Solution:

Known quantities:
The circuit of Figure P9.15: $v_S(t) = 10\sin(2{,}000\pi t)$.

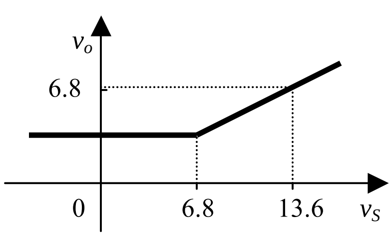
Find:
The output waveform and the voltage transfer characteristic.

Assumptions:
The diode has an offset $V_\gamma = 0.6$ V.

Analysis:



For v_S <6.8 V, v_o=4-V_γ= 3.4 V. For $v_S \geq$ 6.8 V, v_o= v_S /2.
The voltage transfer characteristic is



Problem 9.17

Solution:

Known quantities:

Same as Problem 9.15 but with $v_S(t) = 1.5\sin(2{,}000\pi t)$, the battery equal to 1 V and the resistors of 1kΩ.

Find:

The output waveform and the voltage transfer characteristic.

Assumptions:

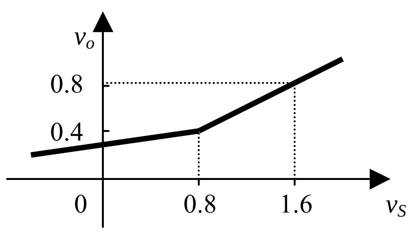
The diode has an offset $V_\gamma = 0.6$ V, and $r_D = 200\ \Omega$.

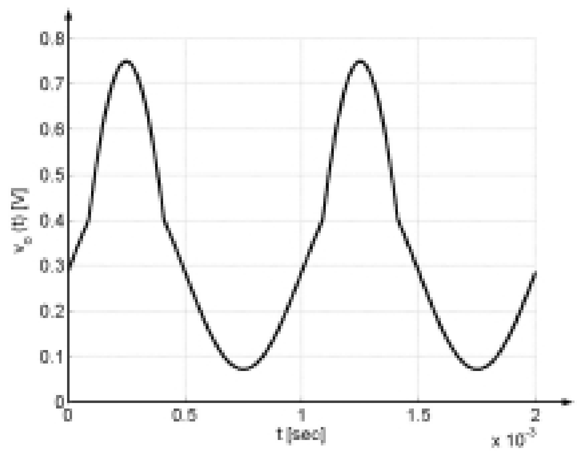
Analysis:

For $v_S < 2(1 - V_\gamma) = 0.8$ V, $v_o = \dfrac{\dfrac{v_S}{1000} + \dfrac{1 - V_\gamma}{r_D}}{\dfrac{1}{1000} + \dfrac{1}{r_D} + \dfrac{1}{1000}} = \dfrac{v_S + 2}{7}$

For $v_S \geq 0.8$ V, $v_o = v_S/2$.

The voltage transfer characteristic is





Problem 9.18

Solution:

Known quantities:

The circuit of Figure P9.18; the diode is fabricated from Silicon and $I_D = I_0\left(e^{\frac{V_D}{V_T}} - 1\right)$. At

$T = 300$ K, $I_0 = 250\ 10^{-12}$ A, $V_T = \dfrac{kT}{q} \approx 26$ mV, $v_S = 4.2\ \text{V} + 110\cos(\omega t)$ mV,

$\omega = 377\ \dfrac{\text{rad}}{\text{s}}$, $R = 7$ kΩ.

Find:

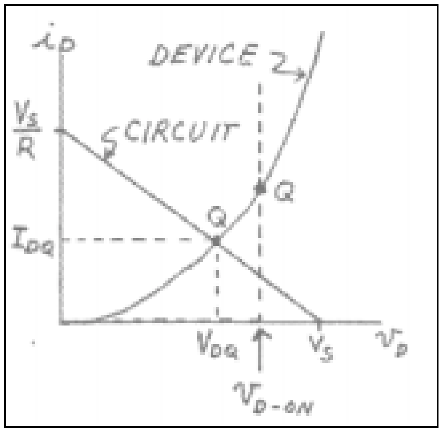
Determine, using superposition, the DC or Q-point current through the diode:

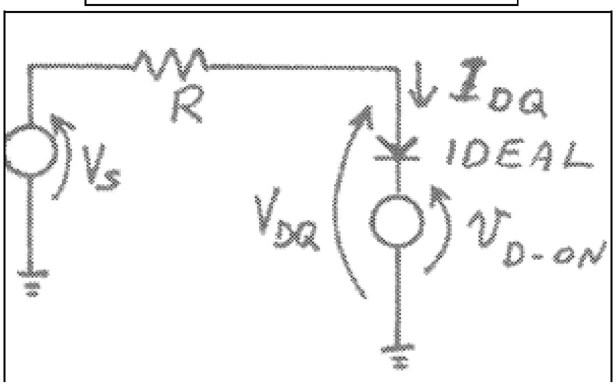
a) Using the DC offset model for the diode.
b) By iteratively solving the circuit characteristic and device characteristic.

Analysis:

a) Suppress the AC component of the source voltage. Construct the DC equivalent circuit using the threshold (or offset voltage model). The Q point is at the intersection of the device (diode) characteristic and the circuit characteristic given by the KVL below. Here, the device characteristic is approximated by the threshold voltage model giving the approximate Q point at the upper right.
Assume the diode is on. Then:

$$V_D = V_{D-on} = 0.7 \text{ V}, \; KVL \quad -V_S + I_{DQ}R + V_D = 0, \; I_{DQ} = \frac{V_S - V_{D-on}}{R} = 0.5 \text{ mA}$$





b) In the forward biased region with significant conduction:

Device: $I_D = I_0 e^{\frac{V_D}{V_T}}, \; V_D = V_T \ln \frac{I_D}{I_0},$ Circuit, KVL: $-V_S + I_D R + V_D = 0,$

$$I_D = \frac{V_S - V_D}{R}$$

A simultaneous solution (the lower left Q point) of the device and circuit characteristics is required. To do this iteratively, initially assume a value for the diode voltage, say 0.7 V for a Silicon device. Then:
1. Using the initial or new diode voltage and the circuit characteristic, determine a new diode current.
2. Using this new diode current and the device characteristic, determine a new diode voltage.
ITERATE or REPEAT until convergence is obtained.

Voltage	New Current	New Voltage
700 mV	0.5 ma	377.2 mV
377.2 mV	0.5461 ma	379.5 mV
379.5 mV	0.5458 ma	379.5 mV <<< Convergence

Convergence is obtained after only 3 iterations and:

$I_{DQ} = 546\ \mu\text{A}\ ,\ V_{DQ} = 379.5\ \text{mV}$

This is a much more accurate solution than that of Part a). The two solutions differ significantly because the reverse saturation current given is atypically large.

Problem 9.19

Solution:

Known quantities:

The circuit of Figure P9.18; the diode is fabricated from Silicon and $I_D = I_0\left(e^{\frac{V_D}{V_T}} - 1\right)$. At

$T = 300\ \text{K}\ ,\ I_0 = 2.03\ 10^{-15}\ \text{A}\ ,\ V_T = \dfrac{kT}{q} \approx 26\ \text{mV}\ ,\ v_S = 5.3\ \text{V} + 7\cos(\omega t)\ \text{mV}\ ,$

$\omega = 377\ \dfrac{\text{rad}}{\text{s}}\ ,\ R = 4.6\ \text{k}\Omega\ .$

Find:

Determine, using superposition and the offset voltage model for the diode, the DC or Q-point current through the diode.

Analysis:

Suppress the AC component of the source voltage. Construct the DC equivalent circuit using the threshold (or offset voltage model). The Q point is at the intersection of the device (diode) characteristic and the circuit characteristic given by the KVL below. Here, the device characteristic is approximated by the threshold voltage model giving the approximate Q point at the upper right.

The DC source voltage will tend to make the diode conduct. Assume the diode is on. Then:

$V_D = V_{D-on} = 0.7\ \text{V}\ ,\ KVL \quad -V_S + I_{DQ}R + V_D = 0\ ,\ I_{DQ} = \dfrac{V_S - V_{D-on}}{R} = 1.0\ \text{mA}$

The current is positive so the assumption above that the diode is on is valid.

Problem 9.20

Solution:

Known quantities:

The circuit of Figure P9.18; the diode is fabricated from Silicon and $I_D = I_0\left(e^{\frac{V_D}{V_T}} - 1\right)$. At

$T = 300\ \text{K}\ ,\ I_0 = 250\ 10^{-12}\ \text{A}\ ,\ V_T = \dfrac{kT}{q} \approx 26\ \text{mV}\ ,\ v_S = 4.2\ \text{V} + 110\cos(\omega t)\ \text{mV}\ ,$

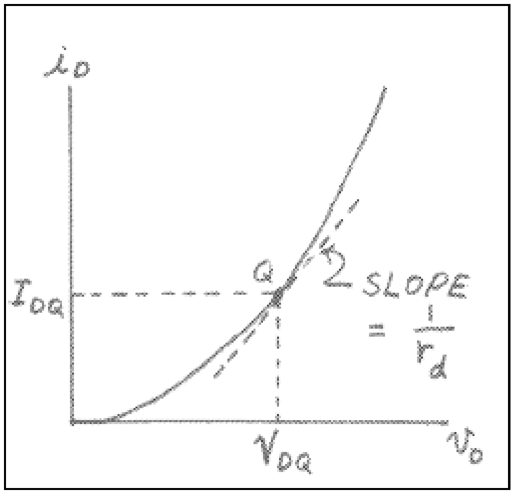
$\omega = 377\ \dfrac{\text{rad}}{\text{s}}\ ,\ R = 7\ \text{k}\Omega$. The DC operating point is: $I_{DQ} = 0.546\ \text{mA}\ ,\ V_{DQ} = 379.5\ \text{mV}$.

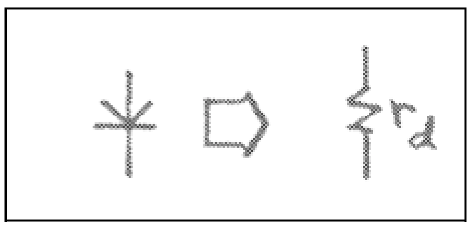
Find:

The equivalent small-signal AC resistance of the diode at room temperature at the Q point given.

Analysis:

$$r_D = \left.\frac{dV_D}{dI_D}\right|_Q = \frac{1}{\left.\frac{dI_D}{dV_D}\right|_Q} = \frac{1}{\left.\frac{1}{V_T} I_0 e^{\frac{V_D}{V_T}}\right|_Q} \approx \left.\frac{V_T}{I_D}\right|_Q = \frac{V_T}{I_{DQ}} = 47.64\ \Omega$$





Problem 9.21

Solution:

Known quantities:

The circuit of Figure P9.18; the diode is fabricated from Silicon and $I_D = I_0\left(e^{\frac{V_D}{V_T}} - 1\right)$. At

$T = 300\ \text{K}$, $I_0 = 2.03\ 10^{-15}\ \text{A}$, $V_T = \frac{kT}{q} \approx 26\ \text{mV}$, $v_S = 5.3\ \text{V} + 70\,cos(\omega t)\ \text{mV}$,

$\omega = 377\ \frac{\text{rad}}{\text{s}}$, $R = 4.6\ \text{k}\Omega$. The DC operating point is: $I_{DQ} = 1.0\ \text{mA}$, $V_{DQ} = 0.7\ \text{V}$.

Find:

The equivalent small-signal AC resistance of the diode at room temperature at the Q point given.

Analysis:

$$r_D = \left.\frac{dV_D}{dI_D}\right|_Q = \frac{1}{\left.\frac{dI_D}{dV_D}\right|_Q} = \frac{1}{\left.\frac{1}{V_T} I_0 e^{\frac{V_D}{V_T}}\right|_Q} \approx \left.\frac{V_T}{I_D}\right|_Q = \frac{V_T}{I_{DQ}} = 26\ \Omega$$

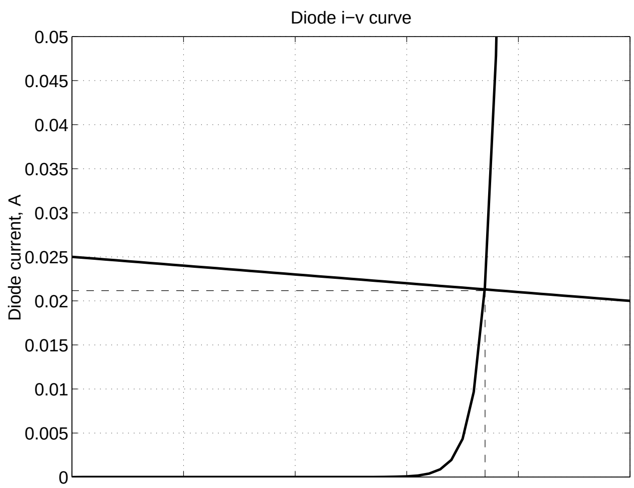
Problem 9.22

Solution:

Known quantities:
A diode with the *i-v* characteristic in Figure 9.8, connected to a 5 V source and a load resistance of 200 Ω.

Find:
a) The load current and voltage
b) The power dissipated by the diode.
c) The load current and voltage if the load is changed to 100 Ω and 500 Ω.

Analysis:
a) The operating point can be determined by using the load-line analysis



The load line is

$$i_D = \frac{5 - v_D}{R_L} = \frac{5}{200} - \frac{v_D}{200}$$

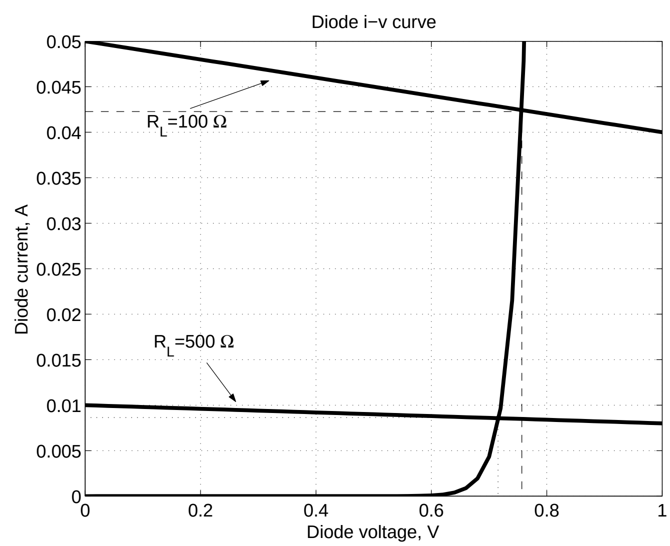
The load voltage is

$$v_L = 5 - v_D \cong 5 - 0.74 = 4.26 \text{ V}$$

The load current is obtained by the figure as intersection of the two characteristics and is equal to 0.021 A.

b) The power dissipated by the diode is

$$P_D = v_D i_D = 0.74 \cdot 0.021 = 15 \text{ mV}$$



c) For R_L=100 Ω, we have

$$v_D \cong 0.757 \text{ V}$$

$$i_D = i_L = \frac{5 - 0.757}{100} = 0.0424 \text{ A}$$

$$v_L = 5 - 0.757 = 4.24 \text{ V}$$

Similarly, for R_L = 500 Ω, we have

$$v_D \cong 0.717 \text{ V}$$

$$i_D = i_L = \frac{5 - 0.717}{100} = 0.04283 \text{ A}$$

$$v_L = 5 - 0.717 = 4.283 \text{ V}$$

Problem 9.23

Solution:

Known quantities:
A diode with the *i-v* characteristic in Figure 9.32, connected in series to a 2 V source and a load resistance of 200 Ω.

Find:
a) The load current and voltage
b) The power dissipated by the diode.
c) The load current and voltage if the load is changed to 100 Ω and 300 Ω.

Analysis:
a) The operating point can be determined by using the load-line analysis
The load line is

$$i_D = \frac{2 - v_D}{R_L} = \frac{2}{200} - \frac{v_D}{200} = 0.01 - 0.005\, v_D$$

By drawing this line on the top of Figure 9.32, the following operating point is obtained

$$i_D = i_L \approx 6 \text{ mA}; \quad v_D \approx 0.73 \text{ V} \Rightarrow v_L = 2 - v_D = 2 - 0.73 = 1.27 \text{ V}$$

b) $P_D = v_D i_D = 0.73 \cdot 0.006 = 4.38 \text{ mV}$

c) For R_L=100 Ω, we have

$$v_D \approx 0.825 \text{ V}$$

$$i_D = i_L \cong \frac{2 - 0.825}{100} = 11.75 \text{ mA}$$

$$v_L \approx 2 - 0.825 = 1.175 \text{ V}$$

For R_L=300 Ω, we have

$$v_D \approx 0.7 \text{ V}$$

$$i_D = i_L \cong \frac{2 - 0.7}{100} = 4.3 \text{ mA}$$

$$v_L \approx 2 - 0.7 = 1.3 \text{ V}$$

Problem 9.24

Solution:

Known quantities:

The circuit of Figure P9.18; the diode is fabricated from Silicon and $I_D = I_0\left(e^{\frac{V_D}{V_T}} - 1\right)$. At

$T = 300 \text{ K}$, $I_0 = 250\ 10^{-12} \text{ A}$, $V_T = \frac{kT}{q} \approx 26 \text{ mV}$, $v_S = 4.2 \text{ V} + 110 cos(\omega t) \text{ mV}$,

$\omega = 377 \frac{\text{rad}}{\text{s}}$, $R = 7\ \text{k}\Omega$. The DC operating point is: $I_{DQ} = 0.548\ \text{mA}$, $V_{DQ} = 0.365\ \text{V}$, $r_d = 47.45\ \Omega$.

Find:
Determine, using superposition the AC voltage across the diode and the AC current through it.

Analysis:
Suppress the DC component of the source voltage. Replace the diode with its AC equivalent resistance; then:

$$V_d = V_S \frac{r_d}{R + r_d}$$

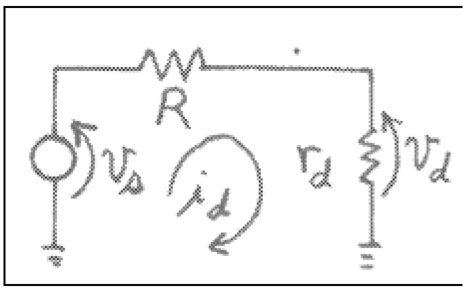
$$V_d = 110\angle 0° \frac{47.45}{7{,}000 + 47.45} = 740.6\angle 0°\ \mu\text{ V},\ v_d(t) = 740.6 cos(\omega t)\ \mu\text{ V}$$

$$I_d = \frac{V_d}{r_d} = \frac{740.6\angle 0°}{47.45} = 15.61\angle 0°\ \mu\text{ A},\ i_d = 15.61 cos(\omega t)\ \mu\text{ A}.$$

The total solution is then:

$$i_d = 0.548\ 10^{-3} + 15.61 cos(\omega t)\ 10^{-6}\ \text{A}$$

$$v_d(t) = 0.365 + 740.6 cos(\omega t)\ 10^{-6}\ \text{V}$$



Problem 9.25

Solution:

Known quantities:
The circuit of Figure P9.25. The diode is fabricated from Silicon and $R = 2.2\ \text{k}\Omega,\ V_{S2} = 3\ \text{V}$.

Find:
The minimum value of V_{S1} at and above which the diode will conduct with a significant current.

Analysis:
A diode fabricated from silicon will conduct with a significant current if it has a forward bias equal to or larger than about 0.7 V.

$KVL \quad -V_{S1} + I_D R + V_D + V_{S2} = 0$, $V_{S1} = I_D R + V_D + V_{S2}$.

At point of conduction:

$I_D = 0$, $V_D = V_{D-on} = 0.7\ \text{V}$, $V_{S1} = 0 + 0.7 + 3 = 3.7\ \text{V}$

Section 9.4: Rectifier Circuits

Problem 9.26

Solution:

Known quantities:
The circuit of Figure P9.26. The input voltage is sinusoidal with an amplitude of 5 V.

Find:
The average value of the output voltage.

Assumptions:
$V_\gamma = 0.7\text{ V}$.

Analysis:
The capacitor will charge to $5\text{ V} - 0.7\text{ V} = 4.3\text{ V}$ and, therefore, the input sine wave will be shifted up 4.3 V to produce the output. As a result, after the cycle (the capacitor builds up its stored charge during the third quarter cycle), the average value of the output will be 4.3 V.

Problem 9.27

Solution:

Known quantities:
The rectifier circuit of Figure P9.27; $v(t) = A\sin(2\pi 100t)\text{ V}$. The conduction must begin during each positive half-cycle at an angle no greater than $5°$.

Find:
The minimum peak value A that the AC source must produce.

Assumptions:
$V_\gamma = 0.7\text{ V}$.

Analysis:

$$A_{min}\sin(5^\circ) = 0.7 \Rightarrow A_{min} = \frac{0.7}{\sin(5^\circ)} = \frac{0.7}{0.0872} = 8.03V$$

Problem 9.28

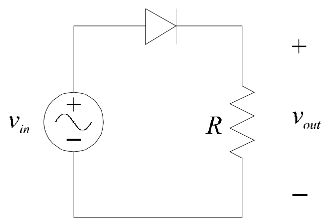
Solution:

Known quantities:
A half-wave rectifier is to provide an average voltage of 50 V at its output.

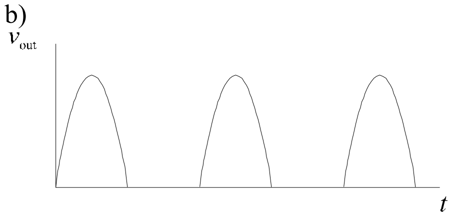
Find:
a) Draw a schematic diagram of the circuit.
b) Sketch the output voltage waveshape.
c) Determine the peak value of the input voltage.
d) Sketch the input voltage waveshape.
e) The rms voltage at the input.

Analysis:

a)



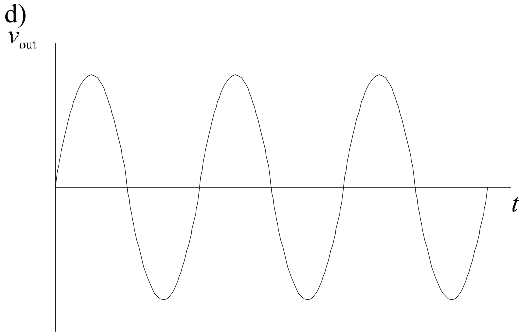
b)



c)

$$v_{ave} = 0.318 v_{peak} = 50 \Rightarrow v_{peak} = 157.2 \text{ V}$$

d)



e)

$$V_{in_{rms}} = \frac{157.2}{\sqrt{2}} = 111.2 \text{ V}$$

Problem 9.29

Solution:

Known quantities:
A rectifier circuit similar to that of Figure 9.25. Load Resistance 100 Ω, AC source voltage 30 V (rms).

Find:
The peak and average current in the load.

Assumptions:
Ideal diode.

Analysis:
The peak voltage is

$$V_{R_{peak}} = 30\sqrt{2} \text{ V} \Rightarrow I_{R_{peak}} = \frac{V_{R_{peak}}}{R} = \frac{30\sqrt{2}}{100} = 0.424 \text{ A}$$

The average current in the load is

$$I_{R_{AV}} = \frac{I_{R_{peak}}}{\pi} = 0.135 \text{ A}$$

Problem 9.30

Solution:

Known quantities:
A rectifier circuit similar to that of Figure 9.25. Load Resistance 220 Ω, AC source voltage 25 V (rms).

Find:
The peak and average current in the load.

Assumptions:
Ideal diode.

Analysis:
The peak voltage is

$$V_{R_{peak}} = 25\sqrt{2} \text{ V} \Rightarrow I_{R_{peak}} = \frac{V_{R_{peak}}}{R} = \frac{25\sqrt{2}}{220} = 0.161 \text{ A}$$

The average current in the load is

$$I_{R_{AV}} = \frac{I_{R_{peak}}}{\pi} = 51.8 \ m\text{A}$$

Problem 9.31

Solution:

Known quantities:
The full-wave power supply of Figure P9.31. The diodes are 1N461 with a rated peak reverse voltage equal to 25 V, and are fabricated from Silicon. $n = 0.05883$, $C = 80 \ \mu\text{F}$, $V_{line} = 170 cos(377t)$ V.

Find:
a) The actual peak reverse voltage across each diode.
b) The reasons for which these diodes are or are not suitable for the specification given.

Analysis:
a) At $\omega t = 0, D1$ is on. At $\omega t = \pi, D1$ is off and the reverse voltage across it is maximum.

$$V_{so} = V_{io} n = 170\,0.05883 = 10 \text{ V}$$

$$KVL: \quad -v_{s1}(t) + v_{D1} + v_L(t) = 0$$

At $\omega t = 0, \ -V_{so} + V_{D-on} + V_m = 0 \Rightarrow V_m = V_{so} - V_{D-on} = 10 - 0.7 = 9.3 \text{ V}$

At $\omega t = \pi, \ -(-V_{so}) + V_{D1} + V_m = 0 \Rightarrow V_{D1} = -V_{so} - V_m = -10 - 9.3 = -19.3 \text{ V}$

b) The actual peak reverse voltage (19.3 V) is less than the rated peak reverse voltage (25 V) by a barely adequate margin of safety. Therefore, the diodes are suitable for the specifications given.

Problem 9.32

Solution:

Known quantities:
The full-wave power supply of Figure P9.31; $n = 0.05883$, $C = 80 \ \mu\text{F}$, $V_{line} = 170 cos(377t)$ V.

The diodes are 1N4727 switching diodes fabricated from Silicon and with the following rated performances: $P_{max} = 500 \text{ mW}$ at $T = 25\ °\text{C}$; derated $3\ \frac{\text{mW}}{°\text{C}}$ $T = 25 \div 125\ °\text{C}$ and $4\ \frac{\text{mW}}{°\text{C}}$ $T = 125 \div 175\ °\text{C}$; $V_{pk-rev} = 30 \text{ V}$.

Find:

a) The actual peak reverse voltage across each diode.
b) The reasons for which these diodes are or are not suitable for the specification given.

Analysis:

a) At $\omega t = 0, D1$ is on. At $\omega t = \pi, D1$ is off and the reverse voltage across it is maximum.

$V_{so} = V_{io} n = 170\,0.1 = 17 \text{ V}$

$KVL: \quad -v_{s1}(t) + v_{D1} + v_L(t) = 0$

At $\omega t = 0,\ -V_{so} + V_{D-on} + V_m = 0 \Rightarrow V_m = V_{so} - V_{D-on} = 17 - 0.7 = 16.3 \text{ V}$

At $\omega t = \pi,\ -(-V_{so}) + V_{D1} + V_m = 0 \Rightarrow V_{D1} = -V_{so} - V_m = -17 - 16.3 = -33.3 \text{ V}$

b) The actual peak reverse voltage (33.3 V) is greater than the rated peak reverse voltage (30 V). Therefore, the diodes are not suitable for the specifications given.

Problem 9.33

Solution:

Known quantities:

The full-wave DC power supply of Figure P9.31; the load voltage of Figure P9.33; $I_L = 60 \text{ mA}$, $V_L = 5 \text{ V}$, $V_r = 5\ \%$, $v_{line} = 170 cos(\omega t) \text{ V}$, $\omega = 377\ \frac{rad}{s}$.

Find:

a) The turns ratio.
b) The capacitor C.

Analysis:

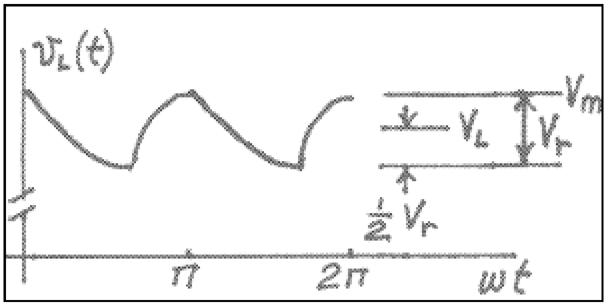
a) $V_m = V_L + \frac{1}{2} V_r = 5 + 0.125 = 5.125 \text{ V}$, $V_{L-min} = V_L - \frac{1}{2} V_r = 5 - 0.125 = 4.875 \text{ V}$,

$V_{s1} = V_{s2} = V_{s0} \, cos(\omega t)$.

$KVL: \quad -v_{s1}(t) + v_{D1} + v_L(t) = 0$

At $\omega t = 0,\ -V_{so} + V_{D-on} + V_L = 0 \Rightarrow V_{s0} = V_{D-on} + V_m = 0.7 + 5.125 = 5.825 \text{ V}$

$$n = \frac{V_{so}}{V_{io}} = 0.0343$$



b) $KVL: \quad v_{s2}(t) + v_{D2} + v_L(t) = 0$.

At $t = t_2$, $V_{so}\, cos(\omega t_2) = -V_{D2-on} - V_{L-min}$. $t_2 = \frac{1}{\omega} cos^{-1}\left(-\frac{V_{D2-on} + V_{L-min}}{V_{so}}\right) = 7.533$ ms.

The exponential discharge of the capacitor can be expressed:

$$v_L(t) = v_L(\infty) + (v_L(0) - v_L(\infty))e^{-\frac{t}{TC}} = 0 + (V_m - 0)e^{-\frac{t}{R_L C}} = V_m e^{-\frac{I_L t}{V_L C}}$$

$$v_L(t_2) = V_{L-min} = V_m e^{-\frac{I_L t_2}{V_L C}}, \; C = -\frac{I_L t_2}{V_L\, ln\left(\frac{V_{L-min}}{V_m}\right)} = 1812\ \mu\text{F}$$

Note: An approximate but conservative value of C can be obtained by using the approximation:

$\omega t_2 \approx \pi$. Then $C \approx -\frac{I_L(\omega t_2)}{\omega V_L\, ln\left(\frac{V_{L-min}}{V_m}\right)} = 2000\ \mu$ F.

This value is conservative because it gives a smaller ripple voltage than that specified.

Problem 9.34

Solution:

Known quantities:

The full-wave DC power supply of Figure P9.31; $I_L = 600$ mA, $V_L = 50$ V, $V_r = 8$ %,

$v_{line} = 170\, cos(\omega t)$ V, $\omega = 377\ \frac{rad}{s}$.

Find:

a) The turns ratio.
b) The capacitor C.

Analysis:

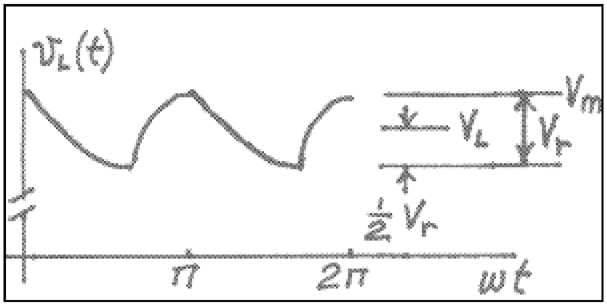
a) $V_m = V_L + \frac{1}{2}V_r = 50 + 2 = 52$ V, $V_{L-min} = V_L - \frac{1}{2}V_r = 50 - 2 = 48$ V,

$V_{s1} = V_{s2} = V_{s0}\, cos(\omega t)$.

$KVL: \quad -v_{s1}(t) + v_{D1} + v_L(t) = 0$

At $\omega t = 0$, $-V_{so} + V_{D-on} + V_L = 0 \Rightarrow V_{s0} = V_{D-on} + V_m = 0.7 + 52 = 52.7$ V

$$n = \frac{V_{so}}{V_{io}} = 0.31$$



b) $KVL: \quad v_{s2}(t) + v_{D2} + v_L(t) = 0$.

At $t = t_2$, $V_{so}\,cos(\omega t_2) = -V_{D2-on} - V_{L-min}$. $t_2 = \frac{1}{\omega}cos^{-1}\left(-\frac{V_{D2-on} + V_{L-min}}{V_{so}}\right) = 7.29$ ms.

The exponential discharge of the capacitor can be expressed:

$$v_L(t) = v_L(\infty) + (v_L(0) - v_L(\infty))e^{-\frac{t}{TC}} = 0 + (V_m - 0)e^{-\frac{t}{R_L C}} = V_m e^{-\frac{I_L t}{V_L C}}$$

$$v_L(t_2) = V_{L-min} = V_m e^{-\frac{I_L t_2}{V_L C}}, \; C = -\frac{I_L t_2}{V_L \, ln\left(\frac{V_{L-min}}{V_m}\right)} = 1093\ \mu\text{F}$$

Problem 9.35

Solution:

Known quantities:

The full-wave DC power supply of Figure P9.31; $I_L = 5$ mA, $V_L = 10$ V, $V_r = 20$ %,

$v_{line} = 170\,cos(\omega t)$ V, $\omega = 377\ \frac{rad}{s}$.

Find:

a) The turns ratio.
b) The capacitor C.

Analysis:

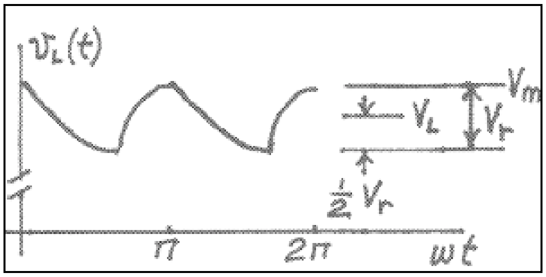
a) $V_m = V_L + \frac{1}{2}V_r = 10 + 1 = 11$ V, $V_{L-min} = V_L - \frac{1}{2}V_r = 10 - 1 = 9$ V,

$V_{s1} = V_{s2} = V_{s0}\,cos(\omega t)$.

$KVL: \quad -v_{s1}(t) + v_{D1} + v_L(t) = 0$

At $\omega t = 0$, $-V_{so} + V_{D-on} + V_L = 0 \Rightarrow V_{s0} = V_{D-on} + V_m = 0.7 + 1 = 6.7$ V

$$n = \frac{V_{so}}{V_{io}} = 0.0688$$



b) $KVL: \quad v_{s2}(t) + v_{D2} + v_L(t) = 0$.

At $t = t_2$, $V_{so}\cos(\omega t_2) = -V_{D2-on} - V_{L-min}$. $t_2 = \frac{1}{\omega}\cos^{-1}\left(-\frac{V_{D2-on} + V_{L-min}}{V_{so}}\right) = 6.76$ ms.

The exponential discharge of the capacitor can be expressed:

$$v_L(t) = v_L(\infty) + (v_L(0) - v_L(\infty))e^{-\frac{t}{TC}} = 0 + (V_m - 0)e^{-\frac{t}{R_L C}} = V_m e^{-\frac{I_L t}{V_L C}}$$

$$v_L(t_2) = V_{L-min} = V_m e^{-\frac{I_L t_2}{V_L C}}, \; C = -\frac{I_L t_2}{V_L \ln\left(\frac{V_{L-min}}{V_m}\right)} = 16.84 \; \mu\text{F}$$

Note: An approximate but conservative value of C can be obtained by using the approximation:

$\omega t_2 \approx \pi$. Then $C \approx -\frac{I_L(\omega t_2)}{\omega V_L \ln\left(\frac{V_{L-min}}{V_m}\right)} = 20.76 \; \mu\text{F}$.

This value is conservative because it gives a smaller ripple voltage than that specified.

Problem 9.36

Solution:

Known quantities:

The full-wave rectifier of Figure P9.36, with a 12 V rms supply.

Find:

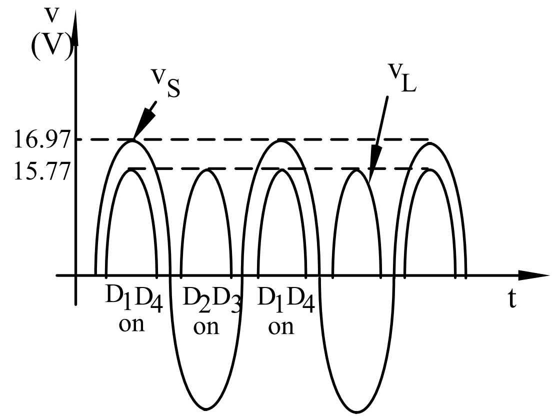
a) Sketch the input source voltage $v_S(t)$, and the output voltage $v_L(t)$, and state which diodes are on and which are off if the diodes have an offset voltage of 0.6 V and the frequency of the source is 60 Hz.

b) Sketch the outpu voltage if $R_L = 1{,}000\ \Omega$ and a capacitor, placed across R_L to provide some filtering, has a value of 8 μF.

c) As part b, with the capacitance equal to 100 μF.

Analysis:

a) The input source voltage is shown below, together with the rectified load voltage. (12 V rms = 16.97 V peak)



b) The time constant, $\tau = CR$, is: $CR = 1000 \cdot 8 \cdot 10^{-6} = 8$ ms.

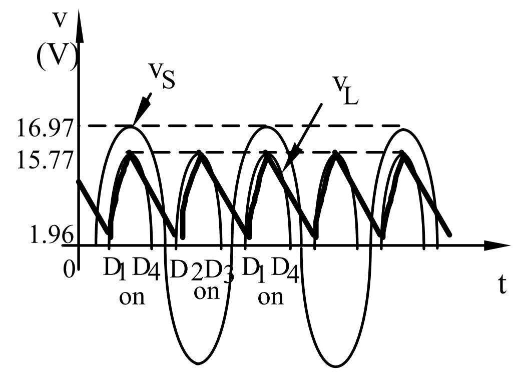
The period of the input sinusoid is: $T = \frac{1}{f} = \frac{1}{60} = 16.7 \text{ ms}$.

Since the capacitor initial voltage is: $v_C(0) = 16.97 - 1.2 = 15.77 \text{ V}$, and the final value is $v_C(\infty) = 0 \text{ V}$

$v_C(t)$ is given by: $v_C(t) = 15.77\, e^{-t/\tau}$.

Therefore, at $t = T$, we have $v_C(T) = 15.77\, e^{-T/\tau} = 1.96 \text{ V}$.

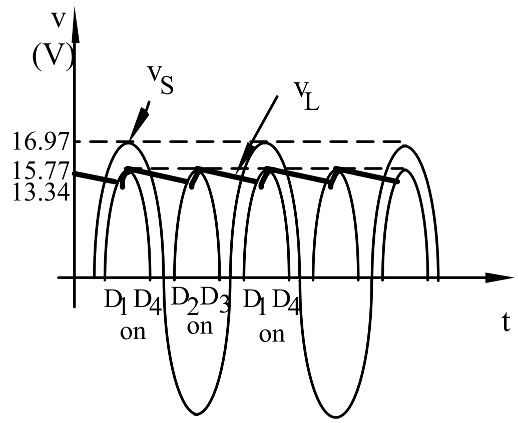
The output waveform is shown below:



(c) The time constant is $CR = 1000 \cdot 100 \cdot 10^{-6} = 100$ ms.

Note that $CR >> T$; $v_C(0) = 16.97 - 1.2 = 15.77 \text{ V}$, and the final value is $v_C(\infty) = 0 \text{ V}$; $v_C(t)$ is given by: $v_C(t) = 15.77\, e^{-t/\tau}$ and therefore $v_C(T) = 15.77\, e^{-T/\tau} = 13.34 \text{ V}$.

The output waveform is shown below.



Problem 9.37

Solution:

Known quantities:
The full-wave bridge power supply of Figure P9.37; the diodes are 1N659 with a rated peak reverse voltage 50 V. $n = 0.2941$, $R_L = 2.5$ kΩ, $C = 700$ μ F, $v_{line} = 170 cos(\omega t)$ V, $\omega = 377 \frac{rad}{s}$.

Find:
a) The actual peak reverse voltage across the diodes.
b) Explain why these diodes are or are not suitable for the specifications given.

Analysis:

a) $v_{line} = nv_{line} = 50 cos(\omega t)$ V, $V_{so} = 50$ V

At $\omega t = 0$, the source voltage has the polarity shown; therefore, $D1$ and $D3$ are conducting, and $D2$ and $D4$ are off. At $\omega t = \pi$, $D1$ and $D3$ are off and the voltage across them is the peak reverse voltage.

$KVL: \quad -v_s(t) + v_{D1} + v_L(t) + v_{D3} = 0$

At $\omega t = 0$: $v_L(0) = V_m = V_{D1} + V_{D3} + V_{so} = 48.6$ V

At $\omega t = \pi$: $v_{D1}(\pi) + v_{D3}(\pi) = V_{so} cos(\pi) - v_L(\pi) = -V_{so} - V_m$

$V_{D1} = V_{D3}$, $V_{D1,3} = \frac{1}{2}(-50 - 48.6) = -49.3$ V

b) The diodes are not suitable because the rated and actual peak reverse voltages are about the same.

Problem 9.38

Solution:

Known quantities:
The full-wave bridge power supply of Figure P9.37; the diodes are T151 with a rated peak reverse voltage 10 V and are fabricated from Silicon. $n = 0.0423$, $V_L = 5.1$ V, $V_r = 0.2$ V, $I_L = 2.5$ mA, $v_{line} = 156 cos(\omega t)$ V, $\omega = 377 \frac{rad}{s}$.

Find:
a) The actual peak reverse voltage across the diodes.
b) Explain why these diodes are or are not suitable for the specifications given.

Analysis:

a) $V_{so} = nV_{io} = 6.6\text{ V}$, $v_s(t) = 6.6\cos(\omega t)\text{ V}$. $V_m = V_L + \frac{1}{2}V_r = 5.2\text{ V}$

At $\omega t = 0$, the source voltage has the polarity shown; therefore, $D1$ and $D3$ are conducting, and $D2$ and $D4$ are off.

$$KVL: \quad -v_s(t) - v_{D4} - v_L(t) - v_{D2} = 0$$

At $\omega t = 0$: $v_{D2}(0) + v_{D4}(0) = -v_L(0) - V_{so}\cos(0) = -V_m - V_{so}$

$$V_{D2} = V_{D4}, \; V_{D2,4} = \frac{1}{2}(-6.6 - 5.2) = -5.9\text{ V}$$

b) The diozes are suitable because the actual PRV (5.9 V) is significantly less than the rated PRV (10 V).

Problem 9.39

Solution:

Known quantities:

The full-wave bridge power supply of Figure P9.37; the diodes are fabricated from Silicon.

$\phi = 23.66\text{ deg}$, $V_L = 10\text{ V}$, $V_r = 1\text{ V}$, $I_L = 650\text{ mA}$, $v_{line} = 170\cos(\omega t)\text{ V}$, $\omega = 377\ \frac{rad}{s}$.

Find:

The value of the average and the peak current through each diode.

Analysis:

Diodes $D1$ and $D3$ will conduct half of the load current and Diodes $D2$ and $D4$ will conduct the other half. Therefore:

$$I_{D-ave} = \frac{1}{2}I_L = 325\text{ mA}$$

The waveforms of the diode currents are complex but can be roughly approximated as triangular (recall area of triangle = bh/2):

$$I_L = \left(I_{D1,3} + I_{D2,4}\right)_{ave} = \frac{1}{2\pi}\int_0^{2\pi}\left(I_{D1,3}(\omega t) + I_{D2,4}(\omega t)\right)d(\omega t) = \frac{1}{2\pi}\left(\frac{\phi I_{D-pk}}{2} + \frac{\phi I_{D-pk}}{2}\right)$$

$$I_{D-pk} = \frac{2\pi I_L}{\frac{1}{2}\phi + \frac{1}{2}\phi} = \frac{2\pi I_L}{\phi} = 1.28\text{ A}$$

Problem 9.40

Solution:

Known quantities:

The full-wave bridge power supply of Figure P9.37; the diodes are fabricated from Silicon. $V_L = 5.3\text{ V}$, $V_r = 0.6\text{ V}$, $I_L = 85\text{ mA}$, $v_{line} = 156\cos(\omega t)\text{ V}$, $\omega = 377\ \frac{rad}{s}$.

Find:

a) The turns ratio n.

b) The capacitor C.

Analysis:

a) First determine the maximum and minimum voltage across the load resistance and capacitor:

$$V_m = V_L + \frac{1}{2}V_r = 5.3 + 0.3 = 5.6 \text{ V},\ V_{L-min} = V_L - \frac{1}{2}V_r = 5.3 - 0.3 = 5 \text{ V}.$$

The amplitude of the supply voltage can now be determined.

$$KVL: \quad -V_{so}\cos(\omega t) + v_{D1} + v_{D3} + v_L(t) = 0$$

At $t = 0,\ -V_{so} + V_{D-on} + V_{D-on} + V_L = 0 \Rightarrow V_{s0} = 2V_{D-on} + V_m = 0.7 + 0.7 + 5.6 = 7 \text{ V}$

$$n = \frac{V_{so}}{V_{io}} = 0.04487$$

b) $KVL: \quad v_s(t) + v_{D2} + v_{D4} + v_L(t) = 0$.

At $t = t_2$, $V_{so}\cos(\omega t_2) = -V_{D-on} - V_{D-on} - V_{L-min}$.

$$\omega t_2 = \cos^{-1}\left(-\frac{2V_{D2-on} + V_{L-min}}{V_{so}}\right) = 2.725 \text{ rad}.$$

The exponential discharge of the capacitor can be expressed:

$$v_L(t) = v_L(\infty) + (v_L(0) - v_L(\infty))e^{-\frac{t}{TC}} = 0 + (V_m - 0)e^{-\frac{t}{R_L C}} = V_m e^{-\frac{I_L \omega t}{\omega V_L C}}$$

$$v_L(t_2) = V_{L-min} = V_m e^{-\frac{I_L \omega t_2}{\omega V_L C}},\ C = -\frac{I_L \omega t_2}{\omega V_L \ln\left(\frac{V_{L-min}}{V_m}\right)} = 1023\ \mu\text{F}$$

Problem 9.41

Solution:

Known quantities:

The full-wave bridge power supply of Figure P9.37; the diodes are fabricated from Silicon. $V_L = 10 \text{ V}$, $V_r = 2.4 \text{ V}$, $I_L = 250 \text{ mA}$, $v_{line} = 156\cos(\omega t) \text{ V}$, $\omega = 377 \ \frac{rad}{s}$.

Find:

a) The turns ratio n.

b) The capacitor C.

Analysis:

a) First determine the maximum and minimum voltage across the load resistance and capacitor:

$$V_m = V_L + \frac{1}{2}V_r = 10 + 1.2 = 11.2 \text{ V},\ V_{L-min} = V_L - \frac{1}{2}V_r = 10 - 1.2 = 8.8 \text{ V}.$$

The amplitude of the supply voltage can now be determined.

$$KVL: \quad -V_{so}\cos(\omega t) + v_{D1} + v_{D3} + v_L(t) = 0$$

At $t = 0,\ -V_{so} + V_{D-on} + V_{D-on} + V_L = 0 \Rightarrow V_{s0} = 2V_{D-on} + V_m = 0.7 + 0.7 + 11.2 = 12.6 \text{ V}$

$$n = \frac{V_{so}}{V_{io}} = 0.08077$$

b) $KVL: \quad v_s(t) + v_{D2} + v_{D4} + v_L(t) = 0$.

At $t = t_2$, $V_{so}\, cos(\omega t_2) = -V_{D-on} - V_{D-on} - V_{L-min}$.

$$\omega t_2 = cos^{-1}\left(-\frac{2V_{D2-on} + V_{L-min}}{V_{so}}\right) = 1.505 \text{ rad}.$$

The exponential discharge of the capacitor can be expressed:

$$v_L(t) = v_L(\infty) + (v_L(0) - v_L(\infty))e^{-\frac{t}{TC}} = 0 + (V_m - 0)e^{-\frac{t}{R_L C}} = V_m e^{-\frac{I_L \omega t}{\omega V_L C}}$$

$$v_L(t_2) = V_{L-min} = V_m e^{-\frac{I_L \omega t_2}{\omega V_L C}}, \; C = -\frac{I_L \omega t_2}{\omega V_L \, ln\left(\frac{V_{L-min}}{V_m}\right)} = 691.3 \; \mu\text{F}$$

Section 9.5: DC Power Supplies, Zener Diodes and Voltage Regulations

Problem 9.42

Solution:

Known quantities:

The piecewise characteristic that passes through the points (-10 V, -5 μA), (0, 0), (0.5 V, 5 mA) and (1 V, 50 mA).

Find:

Determine the piecewise linear model, and, using that model, solve for i and v.

Analysis:

Assume that the diode is forward-biased, and operating in the region between (0.5V, 5mA) and (1V, 50mA). If this is true, then the diode can be modeled by the resistance

$r_D = \frac{\Delta v_D}{\Delta i_D} = \frac{1-0.5}{(50-5)10^{-3}} = \frac{0.5}{4510^{-3}} = 11.11\,\Omega$ in series with a battery having value

$V_{bat} = 0.5 - 510^{-3}(11.11) = 0.444\ \text{V}$.

Then, $i = \frac{2-0.444}{111.11} = 14\ \text{mA}$ and $v = 0.444 + 0.014(11.11) = 0.6\ \text{V}$.

This solution is within the range initially assumed, justifying the assumption.

Problem 9.43

Solution:

Known quantities:

The output voltage at 5.6 V.

Find:

Determine the minimum value of R_L for which the output voltage remains at just 5.6 V.

Analysis:

$$\frac{R_{L_{min}}}{R_{L_{min}}+1800}(18) = 5.6 \Rightarrow 12.4R_{L_{min}} = 10080 \Rightarrow R_{L_{min}} = 812.9\,\Omega$$

Problem 9.44

Solution:

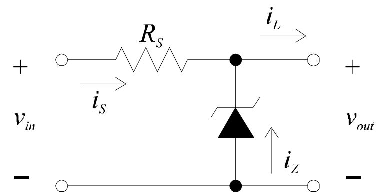
Known quantities:

The output voltage 25 V. The input voltage that varies from 35 to 40 V. The maximum load current is 75 mA. The maximum current, 250 mA, for the Zener diode used.

Find:

Determine the minimum and the maximum value for the series resistance.

Analysis:



$$i_{S_{max}} = \frac{40-25}{R_{S_{min}}}, \ i_{S_{min}} = \frac{35-25}{R_{S_{max}}}, \ i_{Z_{min}} = 0, \ i_{Z_{max}} = -250 \text{ mA}, \ i_L = 75 \text{ mA}$$

$$i_{S_{max}} = 250+75 = 325 \text{ mA} \Rightarrow R_{S_{min}} = \frac{15}{325\times10^{-3}} = 46.2\ \Omega,$$

$$i_{S_{min}} = 0+75 = 75 \text{ mA} \Rightarrow R_{S_{max}} = \frac{10}{75\times10^{-3}} = 133.3\ \Omega$$

Problem 9.45

Solution:

Known quantities:

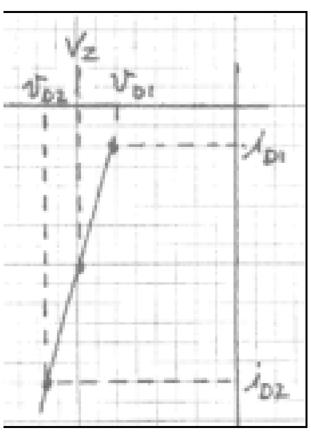
The i-v characteristic of a semiconductor; the minimum current at the "knee" of the curve, 5 mA, and the maximum current, 90 mA.

Find:

Determine the Zener resistance and Zener voltage of the diode.

Analysis:

The Zener voltage is evaluated at the middle of the rated region of operation, ie, midway between the knee of the curve and maximum rated current.



$V_Z = 5$ V

The Zener resistance is determined from the slope of the i-v characteristic over the rated region of operation.

$$r_Z = \frac{1}{Slope} = \frac{1}{\frac{\Delta i_D}{\Delta v_D}} = \frac{\Delta v_D}{\Delta i_D} = \frac{v_{D1}-v_{D2}}{i_{D1}-i_{D2}} = \frac{2}{80\ 10^{-3}} = 25\ \Omega$$

Note: The maximum Zener current is directly related to the maximum power the Zener diode can dissipate without breaking out in smoke and flames. In the specification sheet, either or both may be specified.

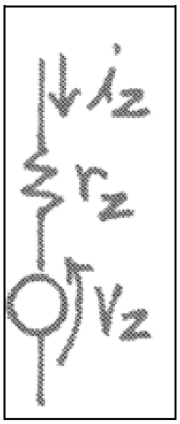
Problem 9.46

Solution:

Known quantities:
The Zener diode used, the 1N5231B; the ripple component of the source voltage, obtained from a DC power supply, $v_S = V_S + V_r$, where $V_S = 20\text{ V}$, $V_r = 250\text{ mV}$, $R = 220\,\Omega$, $I_L = 65\text{ mA}$, $V_L = 5.1\text{ V}$, $R_Z = 17\,\Omega$, $P_{Rated} = 0.5\text{ W}$, $I_{Z-min} = 10\text{ mA}$.

Find:
Determine the maximum rated current the diode can handle without exceeding its power limitation.

Analysis:
Only the rated power is required from the information given. Use the DC model of the Zener. Note that power is dissipated in the equivalent Zener resistance and in the equivalent source. Note the direction of the current and the polarity of the source.



$$P = I_Z^2 R_Z + I_Z V_Z$$

Let $P = P_{Rated}$

Then: $I_Z = I_{Z-max}$

$$P_{Rated} = I_{Z-max}^2 R_Z + I_{Z-max} V_Z$$

$$I_{Z-max} = \frac{1}{2}\left(-\frac{V_Z}{R_Z}\right) \pm \frac{1}{2}\left(\left(\frac{V_Z}{R_Z}\right)^2 - 4\frac{P_{Rated}}{R_Z}\right)^{1/2} = -150 \pm 227.8 = 77.8\text{ mA}$$

where the negative answer is rejected because the Zener current by definition flows in the direction shown.

Problem 9.47

Solution:

Known quantities:
The Zener diode used, the 1N963; $V_Z = 12\text{ V}$, $R_Z = 11.5\,\Omega$, $P_{Rated} = 0.4\text{ W}$, and at the knee of the curve, $i_{ZK} = 0.25\text{ mA}$, $r_{ZK} = 700\,\Omega$.

Find:
Determine the maximum rated current the diode can handle without exceeding its power limitation.

Analysis:
Only the rated power is required from the information given. Use the DC model of the Zener. Note that power is dissipated in the equivalent Zener resistance and in the equivalent source. Note the direction of the current and the polarity of the source.

$P = I_Z^2 R_Z + I_Z V_Z$. Let $P = P_{Rated}$

Then: $I_Z = I_{Z-max}$, $P_{Rated} = I_{Z-max}^2 R_Z + I_{Z-max} V_Z$

$$I_{Z-max} = \frac{1}{2}\left(-\frac{V_Z}{R_Z}\right) \pm \frac{1}{2}\left(\left(\frac{V_Z}{R_Z}\right)^2 - 4\frac{P_{Rated}}{R_Z}\right)^{1/2} = -521.5 \pm 554.1 = 32.6\text{ mA}$$

where the negative answer is rejected because the Zener current by definition flows in the direction shown.

Problem 9.48

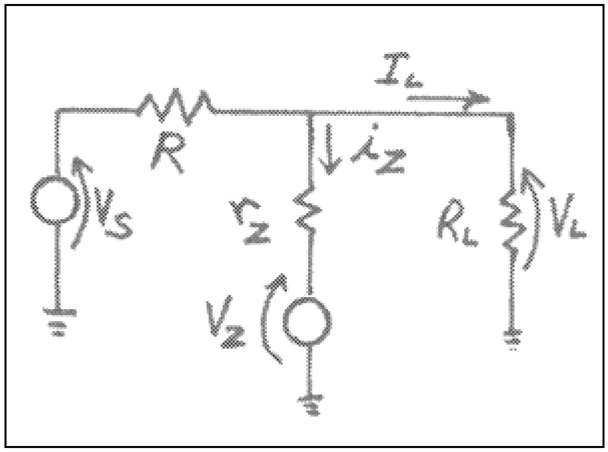
Solution:

Known quantities:

$V_Z = 5\ \text{V} \pm 10\%$, $R_Z = 15\,\Omega$, $I_{Z-min} = 3.5$ mA, $I_{Z-max} = 80$ mA, $V_S = 12 \pm 3$ V,
$I_L = 70 \pm 20$ mA.

Find:
Determine the maximum and minimum value of R to maintain the Zener diode current within its specified limits.

Analysis:
Construct DC equivalent circuit:



$$KCL \quad \frac{V_L - V_S}{R} + I_Z + I_L = 0$$

$$KVL \quad -V_Z - I_Z R_Z + V_L = 0$$

Then:

$$V_L = V_Z + I_Z R_Z$$

$$R = \frac{V_S - V_L}{I_Z + I_L} = \frac{V_S - V_Z - I_Z R_Z}{I_Z + I_L}$$

A maximum Zener current is caused by:
- Minimum value of R
- Maximum source voltage
- Minimum load current
- Minimum Zener voltage.

$$R_{\min} = \frac{V_{S-\max} - V_{Z-\min} - I_{Z-\max} R_Z}{I_{Z-\max} + I_{L-\min}} = 71.54\ \mathbf{\Omega}$$

A minimum Zener current is caused by:
- Maximum value of R
- Maximum load current
- Minimum source voltage
- Maximum Zener voltage.

$$R_{\max} = \frac{V_{S-\min} - V_{Z-\max} - I_{Z-\min} R_Z}{I_{Z-\min} + I_{L-\max}} = 36.87\ \Omega$$

Note that the minimum value of R **<u>EXCEEDS</u>** the maximum value of R. This means that there is no value of R for which all the specifications will be met under all conditions. A value of R can be chosen but conditions may occur where the Zener current exceeds its maximum value or falls below its minimum value.

This problem can be solved by:
1. Choosing another Zener diode with different minimum and maximum currents.
2. Relaxing the specifications on source voltage and load current.

Note that the relationships between minimum and maximum values ALWAYS STARTS WITH THE QUESTION OF WHAT WILL CAUSE A MINIMUM OR MAXIMUM ZENER CURRENT !!! If the Zener current exceeds its maximum rated value, it will burn up; if it falls below its minimum value, the diode will leave the Zener region and cease to regulate the voltage. These represent WORST CASE conditions, a procedure frequently used in design.

Note that a Zener diode acts like an electrical "surge tank" for current; however, the analogy is not exact. A liquid surge tank regulates, ie, maintains constant, pressure and fluid flow rates. It does this by temporarily storing excess fluid when flow rates increase or supplying extra fluid when flow rates decrease. The Zener "surge tank" primarily regulates load voltage as the load resistance [and therefore the load current] or source voltage [and therefore the current supplied by the source] changes. It temporarily "stores" excess current when load current decreases or source voltage increases and "supplies" extra current when load current increases or source voltage decreases.

Problem 9.49

Solution:

Known quantities:
Circuit shown in Figure P9.46,
$V_Z = 12 \text{ V} \pm 10\%$, $R_Z = 9\,\Omega$, $I_{Z-min} = 3.25 \text{ mA}$, $I_{Z-max} = 80 \text{ mA}$, $V_S = 25 \pm 1.5 \text{ V}$,
$I_L = 31 \pm 21.5 \text{ mA}$.

Find:
Determine the maximum and minimum value of R to maintain the Zener diode current within its specified limits.

Analysis:
Construct DC equivalent circuit:

$$KCL \quad \frac{V_L - V_S}{R} + I_Z + I_L = 0, \quad KVL \quad -V_Z - I_Z R_Z + V_L = 0$$

Then:

$$V_L = V_Z + I_Z R_Z, \quad R = \frac{V_S - V_L}{I_Z + I_L} = \frac{V_S - V_Z - I_Z R_Z}{I_Z + I_L}$$

A maximum Zener current is caused by:

Minimum value of R	Maximum source voltage
Minimum load current	Minimum Zener voltage.

$$R_{\min} = \frac{V_{S-\max} - V_{Z-\min} - I_{Z-\max} R_Z}{I_{Z-\max} + I_{L-\min}} = 14.98\ \Omega$$

A minimum Zener current is caused by:

Maximum value of R	Minimum source voltage
Maximum load current	Maximum Zener voltage.

$$R_{\max} = \frac{V_{S-\min} - V_{Z-\max} - I_{Z-\min} R_Z}{I_{Z-\min} + I_{L-\max}} = 184.2\ \Omega$$

Problem 9.50

Solution:

Known quantities:
The diode used, 1N4740A, in the circuit shown in Figure P9.46. $V_Z = 10 \text{ V} \pm 5\%$, $R_Z = 7\,\Omega$,
$I_{Z-min} = 10 \text{ mA}$, $I_{Z-max} = 91 \text{ mA}$, $V_S = 14 \pm 2 \text{ V}$, $R = 19.8\,\Omega$, $P_{Rated} = 1 \text{ W}$.

Find:
Determine the maximum and minimum value of the load current to maintain the Zener diode current within its specified limits.

Analysis:
Construct DC equivalent circuit:

$$KCL \quad \frac{V_L - V_S}{R} + I_Z + I_L = 0, \quad KVL \quad -V_Z - I_Z R_Z + V_L = 0$$

Then:

$V_L = V_Z + I_Z R_Z$, $I_L = \frac{V_S - V_L}{R} - I_Z = \frac{V_S - V_Z - I_Z R_Z}{R} - I_Z$

A minimum and maximum Zener current is caused by [respectively]:

Minimum source voltage	Maximum source voltage
Maximum load current	Minimum load current
Maximum Zener voltage	Minimum Zener voltage

Substituting with these extreme values and solving for the load current:

$$I_{L-max} = \frac{V_{S-min} - V_{Z-max} - I_{Z-min} R_Z}{R} - I_{Z-min} = 62.22 \text{ mA}$$

$$I_{L-min} = \frac{V_{S-max} - V_{Z-min} - I_{Z-max} R_Z}{R} - I_{Z-max} = 205.1 \text{ mA}$$

The minimum load current **EXCEEDS** the maximum load current.

Problem 9.51

Solution:

Known quantities:

The diode used, 1N963, in circuit shown in Figure P9.46. $V_Z = 12 \text{ V} \pm 10\%$, $R_Z = 11.5\,\Omega$, $I_{Z-min} = 2.5 \text{ mA}$, $I_{Z-max} = 32.6 \text{ mA}$, $V_S = 25 \pm 2 \text{ V}$, $R = 470\,\Omega$, $P_{Rated} = 0.4 \text{ W}$.

Find:

Determine the maximum and minimum value of the load current to maintain the Zener diode current within its specified limits.

Analysis:

Construct DC equivalent circuit:

$$KCL \quad \frac{V_L - V_S}{R} + I_Z + I_L = 0, \quad KVL \quad -V_Z - I_Z R_Z + V_L = 0$$

Then:

$$V_L = V_Z + I_Z R_Z, \quad I_L = \frac{V_S - V_L}{R} - I_Z = \frac{V_S - V_Z - I_Z R_Z}{R} - I_Z$$

A minimum and maximum Zener current is caused by [respectively]:

Minimum source voltage	Maximum source voltage
Maximum load current	Minimum load current
Maximum Zener voltage	Minimum Zener voltage

Substituting with these extreme values and solving for the load current:

$$I_{L-max} = \frac{V_{S-min} - V_{Z-max} - I_{Z-min} R_Z}{R} - I_{Z-min} = 18.29 \text{ mA}$$

$$I_{L-min} = \frac{V_{S-max} - V_{Z-min} - I_{Z-max} R_Z}{R} - I_{Z-max} = 1.07 \text{ mA}$$

Problem 9.52

Solution:

Known quantities:

The diode used, 1N4740A, in circuit shown in Figure P9.46. $V_Z = 10 \text{ V} \pm 5\%$, $R_Z = 7\,\Omega$, $I_{Z-min} = 10 \text{ mA}$, $I_{Z-max} = 91 \text{ mA}$, $I_L = 35 \pm 10 \text{ mA}$, $R = 80\,\Omega \pm 5\%$, $P_{Rated} = 1 \text{ W}$.

Find:
Determine the maximum and minimum value of the source voltage to maintain the Zener diode current within its specified limits.

Analysis:
Construct DC equivalent circuit:

$$KCL \quad \frac{V_L - V_S}{R} + I_Z + I_L = 0\,, \; KVL \quad -V_Z - I_Z R_Z + V_L = 0$$

Then:

$$V_L = V_Z + I_Z R_Z \,, V_S = V_L + R(I_Z + I_L) = V_Z + I_Z R_Z + R(I_Z + I_L)$$

Minimum and Maximum Zener currents are caused by [respectively]:

Minimum source voltage.	Maximum source voltage.
Maximum load current.	Minimum load current.
Maximum Zener voltage.	Minimum Zener voltage.
Maximum R.	Minimum R.

Substituting with these extreme values and solving for the source voltage:

$$V_{S-\min} = V_{Z-\max} + I_{Z-\min} R_Z + R_{\max}\left(I_{Z-\min} + I_{L-\max}\right) = 15.19\ V$$

$$V_{S-\max} = V_{Z-\min} + I_{Z-\max} R_Z + R_{\min}\left(I_{Z-\max} + I_{L-\min}\right) = 18.95\ V$$

Problem 9.53

Solution:

Known quantities:
The diode used, 1N4740A, in circuit shown in Figure P9.46. The source voltage is obtained from a DC power supply that has a DC and a ripple component $v_S = V_S + V_r$, where $V_S = 16$ V, $V_r = 2$ V, $I_{Z-min} = 10$ mA, $I_{Z-max} = 91$ mA, $I_L = 35$ mA, $R_Z = 7\,\Omega$, $R = 80\,\Omega$, $V_L = 10$ V, $V_Z = 10$ V.

Find:
Determine the ripple voltage across the load.

Analysis:
Construct the AC equivalent circuit. Suppress the DC component of all voltages and currents in the circuit. Suppress also the DC source in the Zener diode model:

$$R_L = \frac{V_L}{I_L} = 285.7\,\Omega,\; R_{eq} = \frac{R_Z R_L}{R_Z + R_L} = 6.83\,\Omega$$

Note: $v_S = V_r$.

$$V_l = V_L \frac{R_{eq}}{R + R_{eq}} = 157.4 \text{ mV}$$

Problem 9.54

Solution:

Known quantities:
The diode used, 1N5231B, in circuit shown in Figure P9.46. The source voltage is obtained from a DC power supply that has a DC and a ripple component $v_S = V_S + V_r$, where $V_S = 20$ V,

$V_r = 250 \text{ mV}$, $I_{Z-min} = 10 \text{ mA}$, $P_{Rated} = 0.5 \text{ W}$, $I_L = 65 \text{ mA}$, $R_Z = 17\,\Omega$, $R = 220\,\Omega$, $V_L = 5.1 \text{ V}$, $V_Z = 5.1 \text{ V}$.

Find:
Determine the ripple voltage across the load.

Analysis:
Construct the AC equivalent circuit. Note that in this case the load resistance is much smaller than the Zener resistance and will cause a small reduction in the ripple voltage across the load.

$$R_L = \frac{V_L}{I_L} = 78.46\,\Omega, \; R_{eq} = \frac{R_Z R_L}{R_Z + R_L} = 13.97\,\Omega$$

Note: $v_S = V_r$.

$$V_l = V_L \frac{R_{eq}}{R + R_{eq}} = 14.93 \text{ mV}$$

Problem 9.55

Solution:

Known quantities:
The diode used, 1N970, in circuit shown in Figure P9.46. The source voltage is obtained from a DC power supply that has a DC and a ripple component $v_S = V_S + V_r$, where $V_S = 30 \text{ V}$, $V_r = 3 \text{ V}$, $I_{Z-min} = 1.5 \text{ A}$, $I_{Z-max} = 15 \text{ A}$, $I_L = 8 \text{ A}$, $R_Z = 33\,\Omega$, $R = 1\,\Omega$, $V_L = 24 \text{ V}$, $V_Z = 24 \text{ V}$.

Find:
Determine the ripple voltage across the load.

Analysis:
Construct the AC equivalent circuit. Note that in this case the load resistance is much smaller than the Zener resistance and will cause a small reduction in the ripple voltage across the load.

$$R_L = \frac{V_L}{I_L} = 3\,\Omega, \; R_{eq} = \frac{R_Z R_L}{R_Z + R_L} = 2.750\,\Omega$$

Note: $v_S = V_r$.

$$V_l = V_L \frac{R_{eq}}{R + R_{eq}} = 2.2 \text{ V}$$

Section 9.6: Signal Processing Applications

Section 9.7: Photodiodes

Problem 9.56

Solution:

Known quantities:
The range for the input voltage $0 \le v \le 10$ V for the circuit of Figure P9.56.

Find:
Determine the i-v characteristic of the circuit.

Analysis:
With the variables defined in the circuit below, we can compute the following currents:

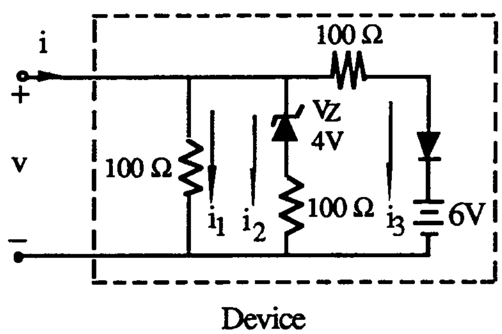
$$I_1 = \frac{v}{100},\ I_2 = \frac{v}{100} \text{ for } v \ge 4 \text{ V},\ I_3 = \frac{v}{100} \text{ for } v \ge 6 \text{ V}$$

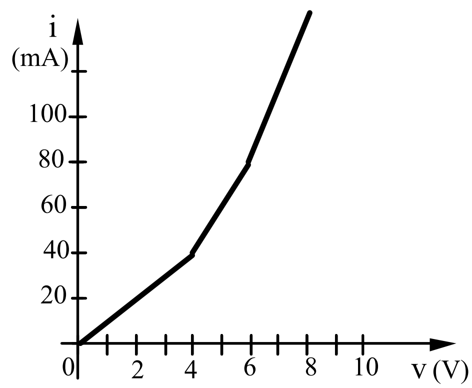
For $0 \le v \le 4$ V, $I = 0.01v$

For $4 \le v \le 6$ V, $I = 0.02v - 0.04$

For $6 \le v \le 10$ V, $I = 0.03v - 0.1$

The resulting i-v characteristic is shown below:





Problem 9.57

Solution:

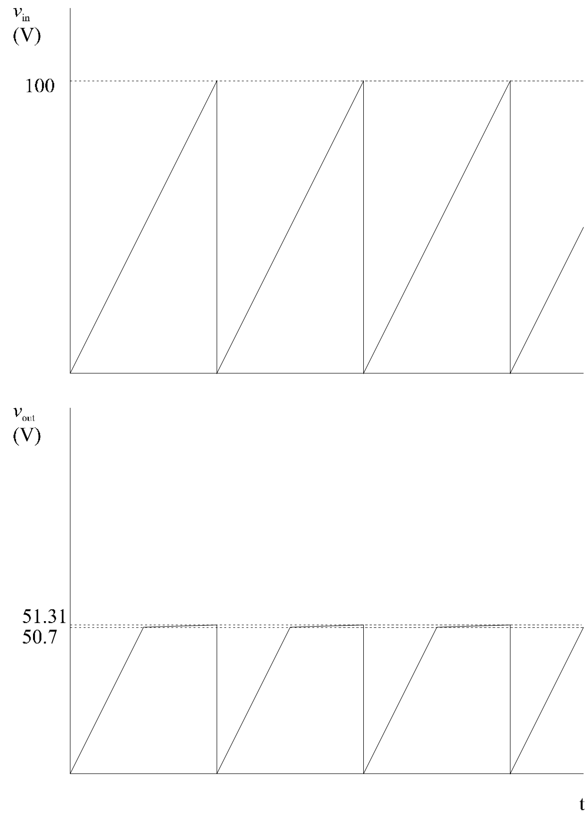
Known quantities:
The input voltage waveform and the circuit of Figure P9.57.

Find:
Determine the output voltage.

Analysis:
For $v_{in} < 50.7$ V, $v_{out} = v_{in}$.

When $v_{in} \ge 50.7$ V, $v_{out} = 50.7 + \frac{0.6}{98 + 0.6} v_{in} = 50.7 + \left(6.085 \times 10^{-3}\right) v_{in}$

The input and output voltage waveforms are sketched below:



Problem 9.58

Solution:

Known quantities:

The circuit of Figure P9.58 where the switch is close at time $t = t_1$.

Find:

The currents I_S, I_B, I_{SW} for the following conditions:

a) $t = t_1^-$, b) $t = t_1^+$, c) what will happen to the battery after the switch closes.

Repeat all considering the circuit of Figure P9.58(b) if the diode has an offset voltage of 0.6 V.

Analysis:

For Figure P9.58 (a):

a) At $t = t_1^-$, before the switch S_1 closes, we have

$$I_{SW} = 0,\ I_S = I_B = \frac{V_S - V_{Battery}}{R_S + R_B} = 0.31 \text{ A}$$

b) At $t = t_1^+$, we have

$$I_S = 13 \text{ A},\ I_B = -0.96 \text{ A},\ I_{SW} = I_S - I_B = 13.96 \text{ A}$$

c) The battery voltage will drop quickly because of the small resistance in the circuit.

For Figure P9.58 (b):

a) At $t = t_1^-$, we have

$$I_{SW} = 0,\ I_S = I_B = \frac{V_S - V_{Battery} - V_\gamma}{R_S + R_B} = 0.25\ \text{A}$$

b) At $t = t_1^+$, we have

$$I_S = I_{SW} = 13\ \text{A},\ I_B = 0$$

c) The battery will not be drained, because of the large reverse resistance of the diode.

Problem 9.59

Solution:

Known quantities:
The circuit in Figure P9.59. The diode has $V_\gamma = 0.7\ \text{V}$. The input voltage is sinusoidal with an amplitude of 6, 1.5, 0.4 V and zero average value.

Find:
Determine the average value of the output voltage.

Analysis:
The capacitor will charge to $\mathbf{V}_S - 0.7\ \mathbf{V}$.

6 V:
Therefore, the input sine wave will be shifted up 5.3 V to produce the output. As a result, after the cycle (the capacitor builds up its stored charge during the third quarter cycle), the average value of the output will be 5.3 V.

1.5 V:
Therefore, the input sine wave will be shifted up 0.8 V to produce the output. As a result, after the cycle (the capacitor builds up its stored charge during the third quarter cycle), the average value of the output will be 0.8 V.

0.4 V:
Since the input is less than 0.7 V, the capacitor does not charge and the output voltage is 0 V.

Problem 9.60

Solution:

Known quantities:
The LED circuit in Figure 9.14. Diode operating point: V_{LED} =1.7 V; I_{LED}=20 mA; V_S=5 V.

Find:
Determine the LED power consumption and the power required by the voltage source.

Analysis:
The power consumption is

$$P_{\text{LED}} = V_{\text{LED}} I_{\text{LED}} = 34\ \text{mW}$$

The power required at the source is

$$P_S = V_S I_{\text{LED}} = 100\ \text{mW}$$

Problem 9.61

Solution:

Known quantities:
The LED circuit in Figure 9.14. Diode operating point: V_{LED} =1.5 V; I_{LED}=30 mA; V_S=5 V.

Find:
Determine the LED power consumption and the power required by the voltage source.
Analysis:
The power consumption is
$$P_{\text{LED}} = V_{\text{LED}} I_{\text{LED}} = 45 \text{ mW}$$
The power required at the source is
$$P_S = V_S I_{\text{LED}} = 150 \text{ mW}$$