Chapter 1
Introduction to Semiconductors

Section 1-1 The Atom

1. Atoms have a planetary type of structure that consists of a central nucleus surrounded by orbiting electrons. The **nucleus** consists of positively charged particles called **protons** and uncharged particles called **neutrons.**

2. A shell is an energy level in which the orbits of electrons are grouped.

3. An atom with an atomic number of 6 has **6 electrons** and **6 protons**.

4. The third shell of an atom can have $2n^2 = 2(3)^2 = \mathbf{18}$ **electrons**.

Section 1-2 Materials Used in Electronics

5. The materials represented in Figure 1–21 in the textbook are

(a) insulator (b) semiconductor (c) conductor

6. An atom with four valence electrons is a **semiconductor**.

7. In a silicon crystal, each atom forms **four** covalent bonds.

Section 1-3 Current in Semiconductors

8. When heat is added to silicon, more free electrons and holes are produced.

9. Current is produced in silicon at the **conduction** band and the **valence** band.

10. The conduction band is not part of the crystal structure, so there are no holes.

11. The valence electrons are attracted to the positive ions, keeping the positive ions together and forming the **metallic bond**.

Section 1-4 N-Type and P-Type Semiconductors

12. Doping is the carefully controlled addition of trivalent or pentavalent atoms to pure (intrinsic) semiconductor material for the purpose of increasing the number of majority carriers (free electrons or holes).

13. Antimony is a pentavalent (donor) material used for doping to increase free electrons. Boron is a trivalent (acceptor) material used for doping to increase the holes.

Section 1-5 The PN Junction

14. The electric field across the *pn* junction of a diode is created by donor atoms in the *n* region losing free electrons to acceptor atoms in the *p* region. This creates positive ions in the *n* region near the junction and negative ions in the *p* region near the junction. A field is then established between the ions.

15. The barrier potential of a diode represents an energy gradient that must be overcome by conduction electrons and produces a voltage drop, not a source of energy.

Chapter 2
Diodes and Applications

Section 2-1 Diode Operation

1. To forward-bias a diode, the positive terminal of a voltage source must be connected to the ***p* region**.

2. A series resistor is needed to **limit the current** through a forward-biased diode to a value that will not damage the diode because the diode itself has very little resistance.

3. Reverse-bias voltage up to the breakdown value can be applied.

4. The high reverse-bias voltage imparts energy to the free minority electrons so that as they speed through the *p* region, they collide with atoms with enough energy to knock valence electrons out of orbit and into the conduction band. The newly created conduction electrons are also high in energy and repeat the process. If one electron knocks only two others out of their valence orbit during its travel through the *p* region, the numbers quickly multiply. As these high-energy electrons go through the depletion region, they have enough energy to go through the *n* region as conduction electrons, rather than combining with holes.

Section 2-2 Voltage-Current Characteristic of a Diode

5. To generate the forward bias portion of the characteristic curve, connect a voltage source across the diode for forward bias and place an ammeter in series with the diode and a voltmeter across the diode. Slowly increase the voltage from zero and plot the forward voltage versus the current.

6. A temperature increase would cause the barrier potential of a silicon diode to decrease from
0.7 V to 0.6 V.

Section 2-3 Diode Models

7. (a) The diode is reverse-biased.
(b) The diode is forward-biased.
(c) The diode is forward-biased.
(d) The diode is forward-biased.

8. (a) $V_R = 5\text{ V} - 8\text{ V} = \mathbf{-3\ V}$

(b) $V_F = \mathbf{0.7\ V}$

(c) $V_F = \mathbf{0.7\ V}$

(d) $V_F = \mathbf{0.7\ V}$

9. (a) $V_R = 5\text{ V} - 8\text{ V} = \mathbf{-3\ V}$

(b) $V_F = \mathbf{0\ V}$

(c) $V_F = \mathbf{0\ V}$

(d) $V_F = \mathbf{0\ V}$

10. Ignoring r'_R:

(a) $V_R \cong 5\text{ V} - 8\text{ V} = \mathbf{-3\ V}$

(b) $I_F = \dfrac{100\text{ V} - 0.7\text{ V}}{560\ \Omega + 10\ \Omega} = 174\text{ mA}$

$V_F = I_F r'_d + V_B = (174\text{ mA})(10\ \Omega) + 0.7\text{ V} = \mathbf{2.44\ V}$

(c) $I_{tot} = \dfrac{30\text{ V}}{R_{tot}} = \dfrac{30\text{ V}}{4.85\text{ k}\Omega} = 6.19\text{ mA}$

$I_F = \dfrac{6.19\text{ mA}}{2} = 3.1\text{ mA}$

$V_F = I_F r'_d + 0.7\text{ V} = (3.1\text{ mA})(10\ \Omega) + 0.7\text{ V} = \mathbf{0.731\ V}$

(d) Approximately all of the current from the 20 V source is through the diode. No current from the 10 V source is through the diode.

$I_F = \dfrac{20\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega + 10\ \Omega} = 1.92\text{ mA}$

$V_F = (1.92\text{ mA})(10\ \Omega) + 0.7\text{ V} = \mathbf{0.719\ V}$

Section 2-4 Half-Wave Rectifiers

11. See Figure 2-1.

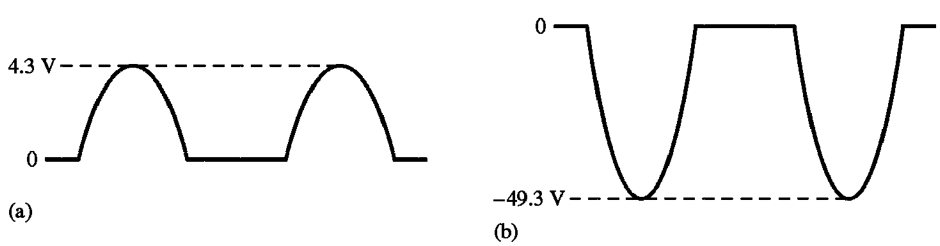

Figure 2-1

12. (a) PIV = V_p = **5 V** (b) PIV = V_p = **50 V**

13. $V_{AVG} = \dfrac{V_p}{\pi} = \dfrac{200\text{ V}}{\pi} = \mathbf{63.7\ V}$

Chapter 2

14. (a) $I_F = \dfrac{V_{(p)in} - 0.7\text{ V}}{R} = \dfrac{5\text{ V} - 0.7\text{ V}}{47\ \Omega} = \dfrac{4.3\text{ V}}{47\ \Omega} = \mathbf{91.5\ mA}$

(b) $I_F = \dfrac{V_{(p)in} - 0.7\text{ V}}{R} = \dfrac{50\text{ V} - 0.7\text{ V}}{3.3\text{ k}\Omega} = \dfrac{49.3\text{ V}}{3.3\text{ k}\Omega} = \mathbf{14.9\ mA}$

15. $V_{sec} = nV_{pri} = (0.2)120\text{ V} = \mathbf{24\ V\ rms}$

16. $V_{sec} = nV_{pri} = (0.5)120\text{ V} = 60\text{ V rms}$

$V_{p(sec)} = 1.414(60\text{ V}) = 84.8\text{ V}$

$V_{avg(sec)} = \dfrac{V_{p(sec)}}{\pi} = \dfrac{84.8\text{ V}}{\pi} = 27.0\text{ V}$

$P_{L(p)} = \dfrac{\left(V_{p(sec)} - 0.7\text{ V}\right)^2}{R_L} = \dfrac{(84.1\text{ V})^2}{220\ \Omega} = \mathbf{32.1\ W}$

$P_{L(avg)} = \dfrac{\left(V_{avg(sec)}\right)^2}{R_L} = \dfrac{(27.0\text{ V})^2}{220\ \Omega} = \mathbf{3.31\ W}$

Section 2-5 Full-Wave Rectifiers

17. (a) $V_{\text{AVG}} = \dfrac{V_p}{\pi} = \dfrac{5\text{ V}}{\pi} = \mathbf{1.59\ V}$

(b) $V_{\text{AVG}} = \dfrac{2V_p}{\pi} = \dfrac{2(100\text{ V})}{\pi} = \mathbf{63.7\ V}$

(c) $V_{\text{AVG}} = \dfrac{2V_p}{\pi} + 10\text{ V} = \dfrac{2(10\text{ V})}{\pi} + 10\text{ V} = \mathbf{16.4\ V}$

(d) $V_{\text{AVG}} = \dfrac{2V_p}{\pi} - 15\text{ V} = \dfrac{2(40\text{ V})}{\pi} - 15\text{ V} = \mathbf{10.5\ V}$

18. (a) Center-tapped full-wave rectifier

(b) $V_{p(sec)} = (0.25)(1.414)120\text{ V} = \mathbf{42.4\ V}$

(c) $\dfrac{V_{p(sec)}}{2} = \dfrac{42.4\text{ V}}{2} = \mathbf{21.2\ V}$

(d) See Figure 2-2. $V_{RL} = 21.2\text{ V} - 0.7\text{ V} = 20.5\text{ V}$

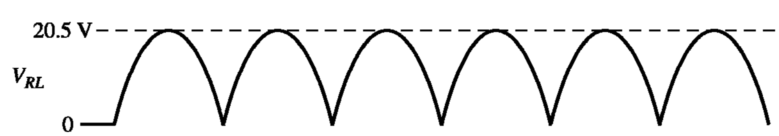

Figure 2-2

(e) $$I_F = \frac{\frac{V_{p(sec)}}{2} - 0.7\text{ V}}{R_L} = \frac{20.5\text{ V}}{1.0\text{ k}\Omega} = \mathbf{20.5\text{ mA}}$$

(f) $\text{PIV} = 21.2\text{ V} + 20.5\text{ V} = \mathbf{41.7\text{ V}}$

19. $$V_{AVG} = \frac{120\text{ V}}{2} = 60\text{ V for each half}$$

$$V_{AVG} = \frac{V_p}{\pi}$$

$$V_p = \pi V_{AVG} = \pi(60\text{ V}) = \mathbf{186\text{ V}}$$

20. See Figure 2-3.

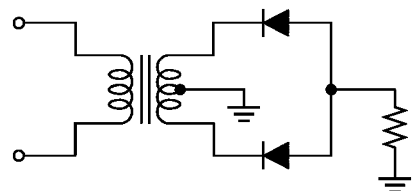

Figure 2-3

21. $$\text{PIV} = V_p = \frac{\pi V_{AVG(out)}}{2} = \frac{\pi(50\text{ V})}{2} = \mathbf{78.5\text{ V}}$$

22. $\text{PIV} = V_{p(out)} = 1.414(20\text{ V}) = \mathbf{28.3\text{ V}}$

23. See Figure 2-4.

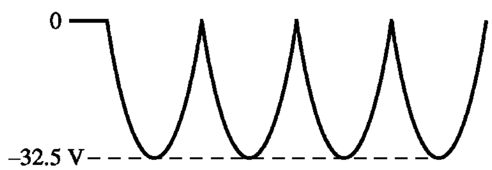

Figure 2-4

Chapter 2

Section 2-6 Power Supply Filters and Regulators

24. $V_{r(pp)} = 0.5\text{ V}$

$$r = \frac{V_{r(pp)}}{V_{\text{DC}}} = \frac{0.5\text{ V}}{75\text{ V}} = \mathbf{0.00667}$$

25. $$V_{r(pp)} = \frac{V_{p(in)}}{fR_LC} = \frac{30\text{ V}}{(120\text{ Hz})(600\ \Omega)(50\ \mu\text{F})} = \mathbf{8.33\ V\ pp}$$

$$V_{\text{DC}} = \left(1 - \frac{1}{2fR_LC}\right)V_{p(in)} = \left(1 - \frac{1}{(240\text{ Hz})(600\ \Omega)(50\ \mu\text{F})}\right)30\text{ V} = \mathbf{25.8\ V}$$

26. $$\%r = \left(\frac{V_{r(pp)}}{V_{\text{DC}}}\right)100 = \left(\frac{8.33\text{ V}}{25.8\text{ V}}\right)100 = \mathbf{32.3\%}$$

27. $V_{r(pp)} = (0.01)\,(18\text{ V}) = 180\text{ mV}$

$$V_{r(pp)} = \left(\frac{1}{fR_LC}\right)V_{p(in)}$$

$$C = \left(\frac{1}{fR_LV_r}\right)V_{p(in)} = \left(\frac{1}{(120\text{ Hz})(1.5\text{ k}\Omega)(180\text{ mV})}\right)18\text{ V} = \mathbf{556\ \mu F}$$

28. $$V_{r(pp)} = \frac{V_{p(in)}}{fR_LC} = \frac{80\text{ V}}{(120\text{ Hz})(10\text{ k}\Omega)(10\ \mu\text{F})} = 6.67\text{ V}$$

$$V_{\text{DC}} = \left(1 - \frac{1}{2fR_LC}\right)V_{p(in)} = \left(1 - \frac{1}{(240\text{ Hz})(10\text{ k}\Omega)(10\ \mu\text{F})}\right)80\text{ V} = 76.7\text{ V}$$

$$r = \frac{V_{r(pp)}}{V_{\text{DC}}} = \frac{6.67\text{ V}}{76.7\text{ V}} = \mathbf{0.087}$$

29. $V_{p(sec)} = (1.414)(36\text{ V}) = 50.9\text{ V}$

$V_{r(rect)} = V_{p(sec)} - 1.4\text{ V} = 50.9\text{ V} - 1.4\text{ V} = 49.5\text{ V}$

Neglecting R_{surge}, $V_{r(pp)} = \left(\frac{1}{fR_LC}\right)V_{p(rect)} = \left(\frac{1}{(120\text{ Hz})(3.3\text{ k}\Omega)(100\ \mu\text{F})}\right)49.5\text{ V} = \mathbf{1.25\ V}$

$$V_{\text{DC}} = \left(1 - \frac{1}{2fR_LC}\right)V_{p(rect)} = V_{p(rect)} - \frac{V_{r(pp)}}{2} = 49.5\text{ V} - 0.625\text{ V} = \mathbf{48.9\ V}$$

30. $V_{p(sec)} = 1.414(36\text{ V}) = 50.9\text{ V}$

See Figure 2-5.

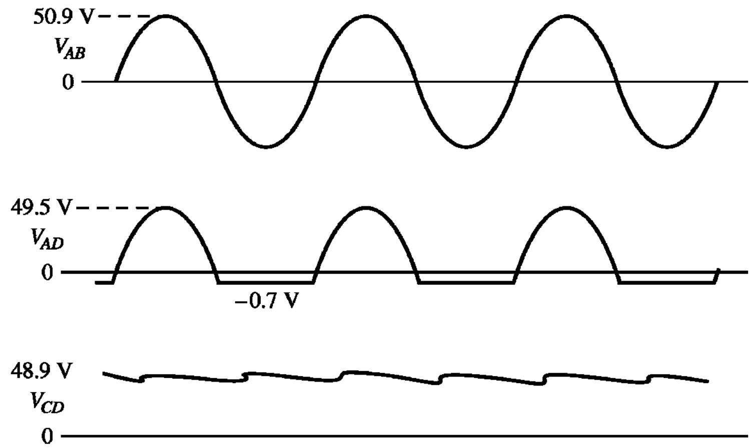

Figure 2-5

31. Load regulation $= \left(\dfrac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}}\right)100\% = \left(\dfrac{15.5\text{ V} - 14.9\text{ V}}{14.9\text{ V}}\right)100\% = \mathbf{4\%}$

32. $V_{\text{FL}} = V_{\text{NL}} - (0.005)V_{\text{NL}} = 12\text{ V} - (0.005)12\text{ V} = \mathbf{11.94\text{ V}}$

Section 2-7 Diode Limiters and Clampers

33. See Figure 2-6.

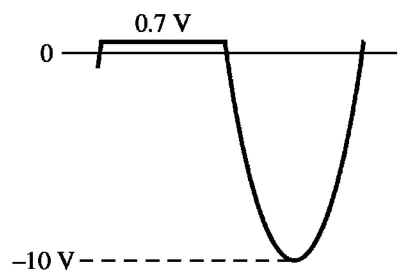

Figure 2-6

34. Apply Kirchhoff's law at the peak of the positive half cycle:

(b) $25\text{ V} = V_{\text{R1}} + V_{\text{R2}} + 0.7\text{ V}$

$2V_{\text{R}} = 24.3\text{ V}$

$V_{\text{R}} = \dfrac{24.3\text{ V}}{2} = 12.15\text{ V}$

$V_{out} = V_{\text{R}} + 0.7\text{ V} = 12.15\text{ V} + 0.7\text{ V} = 12.85\text{ V}$

See Figure 2-7(a).

(c) $V_R = \dfrac{11.3\text{ V}}{2} = 5.65\text{ V}$

$V_{out} = V_R + 0.7\text{ V} = 5.65\text{ V} + 0.7\text{ V} = 6.35\text{ V}$

See Figure 2-7(b).

(d) $V_R = \dfrac{4.3\text{ V}}{2} = 2.15\text{ V}$

$V_{out} = V_R + 0.7\text{ V} = 2.15\text{ V} + 0.7\text{ V} = 2.85\text{ V}$

See Figure 2-7(c).

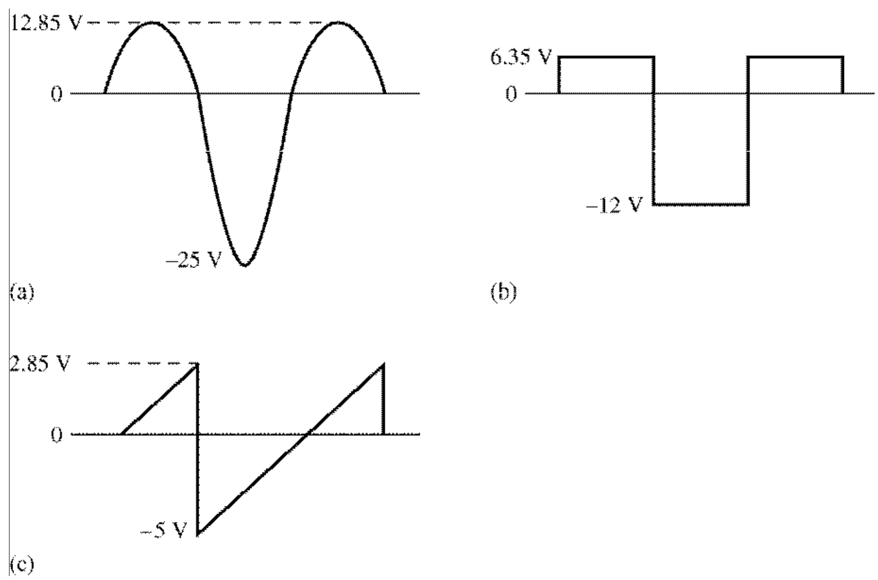

Figure 2-7

35. See Figure 2-8.

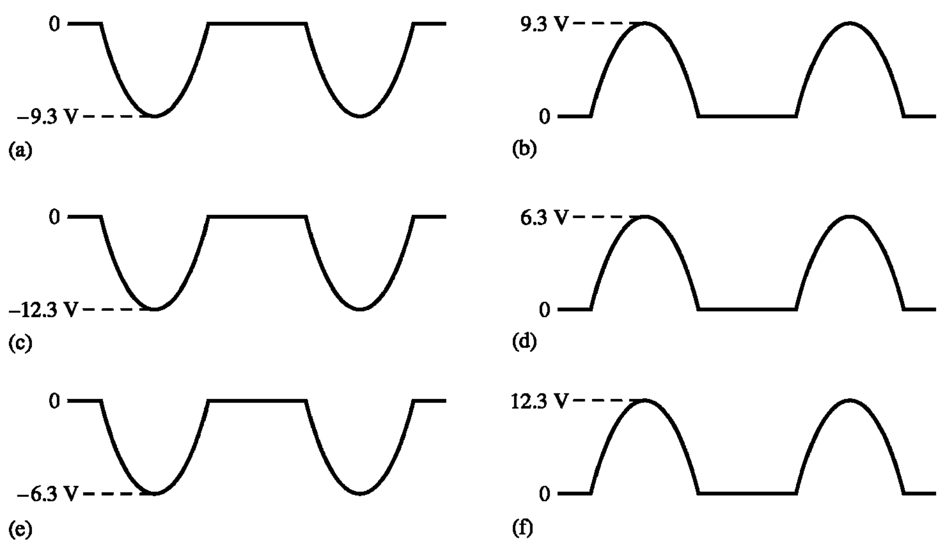

Figure 2-8

36. See Figure 2-9.

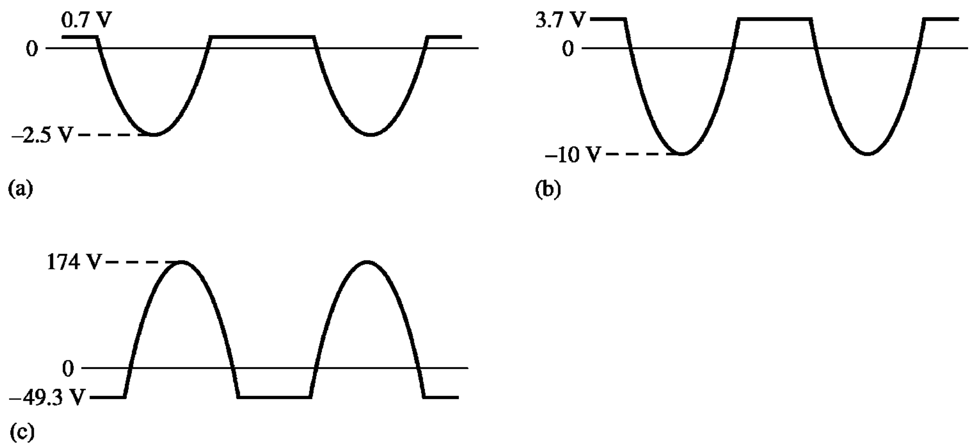

Figure 2-9

37. See Figure 2-10.

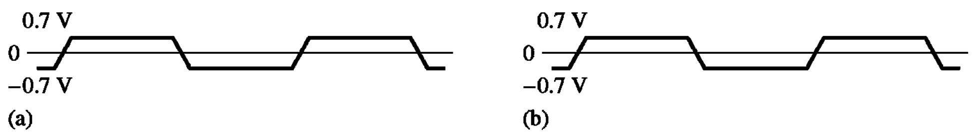

Figure 2-10

38. (a) $I_p = \dfrac{30\text{ V} - 0.7\text{ V}}{2.2\text{ k}\Omega} = \mathbf{13.3\text{ mA}}$

(b) Same as (a).

39. (a) $I_p = \dfrac{30\text{ V} - (12\text{ V} + 0.7\text{ V})}{2.2\text{ k}\Omega} = \mathbf{7.86\text{ mA}}$

(b) $I_p = \dfrac{30\text{ V} - (12\text{ V} - 0.7\text{ V})}{2.2\text{ k}\Omega} = \mathbf{8.5\text{ mA}}$

(c) $I_p = \dfrac{30\text{ V} - (-11.3\text{ V})}{2.2\text{ k}\Omega} = \mathbf{18.8\text{ mA}}$

(d) $I_p = \dfrac{30\text{ V} - (-12.7\text{ V})}{2.2\text{ k}\Omega} = \mathbf{19.4\text{ mA}}$

40. See Figure 2-11.

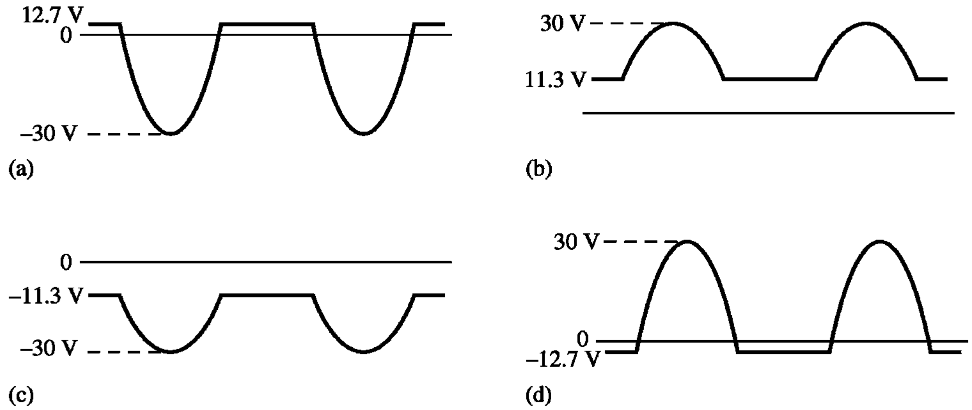

Figure 2-11

41. (a) A sine wave with a positive peak at 0.7 V, a negative peak at -7.3 V, and a dc value of
-3.3 V.

(b) A sine wave with a positive peak at 29.3 V, a negative peak at -0.7 V, and a dc value of
+14.3 V.

(c) A square wave varying from $+0.7$ V to -15.3 V with a dc value of -7.3 V.

(d) A square wave varying from $+1.3$ V to -0.7 V with a dc value of $+0.3$ V.

42. (a) A sine wave varying from -0.7 V to $+7.3$ V with a dc value of +3.3 V.

(b) A sine wave varying from -29.3 V to $+7.3$ V with a dc value of +14.3 V.

(c) A square wave varying from -0.7 V to $+15.3$ V with a dc value of +7.3 V.

(d) A square wave varying from -1.3 V to $+0.7$ V with a dc value of -0.3 V.

Section 2-8 Voltage Multipliers

43. $V_{\text{OUT}} = 2V_{p(in)} = 2(1.414)(20\text{ V}) = \mathbf{56.6\text{ V}}$

See Figure 2-12.

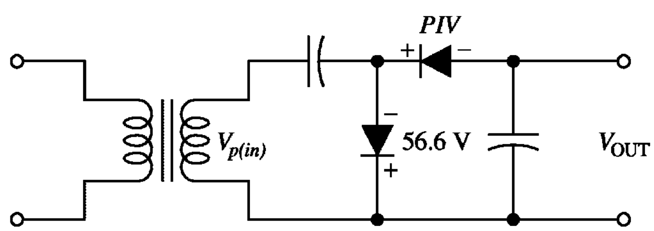

Figure 2-12

44. $V_{\text{OUT}(trip)} = 3V_{p(in)} = 3(1.414)(20\text{ V}) = \mathbf{84.8\text{ V}}$

$V_{\text{OUT}(quad)} = 4V_{p(in)} = 4(1.414)(20\text{ V}) = \mathbf{113\text{ V}}$

See Figure 2-13.

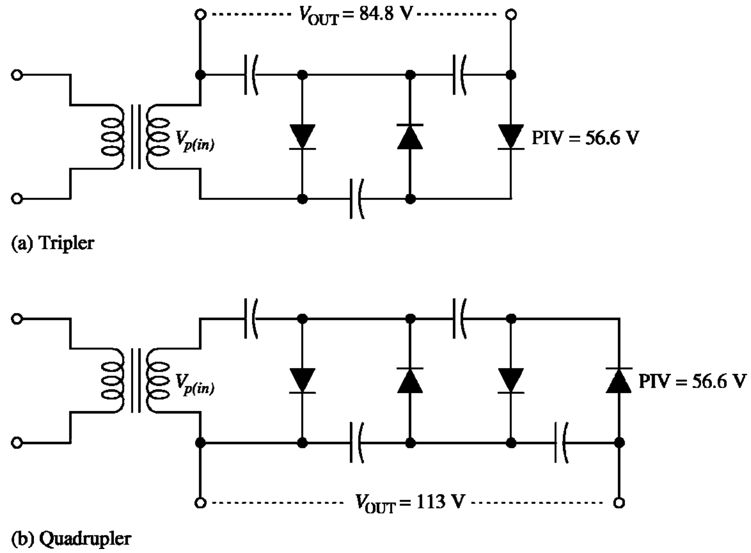

Figure 2-13

Section 2-9 The Diode Datasheet

45. The PIV is specified as the peak repetitive reverse voltage $= \mathbf{100\text{ V}}$.

46. The PIV is specified as the peak repetitive reverse voltage $= \mathbf{1000\text{ V}}$.

47. $I_{\text{F(AVG)}} = 1.0\text{ A}$

$$R_{L(\min)} = \frac{50\text{ V}}{1.0\text{ A}} = \mathbf{50\ \Omega}$$

Section 2-10 Troubleshooting

48. (a) Since $V_{\text{D}} = 25\text{ V} = 0.5V_{\text{S}}$, the diode is **open**.

(b) The diode is forward-biased but since $V_{\text{D}} = 15\text{ V} = V_{\text{S}}$, the diode is **open.**

(c) The diode is reverse-biased but since $V_{\text{R}} = 2.5\text{ V} = 0.5V_{\text{S}}$, the diode is **shorted**.

(d) The diode is reverse-biased and $V_{\text{R}} = 0\text{ V}$. The diode is **operating properly.**

49. $V_{\text{A}} = V_{\text{S1}} = \mathbf{+25\text{ V}}$

$V_{\text{B}} = V_{\text{S1}} - 0.7\text{ V} = 25\text{ V} - 0.7\text{ V} = \mathbf{+24.3\text{ V}}$

$V_{\text{C}} = V_{\text{S2}} + 0.7\text{ V} = 8\text{ V} + 0.7\text{ V} = \mathbf{+8.7\text{ V}}$

$V_{\text{D}} = V_{\text{S2}} = \mathbf{+8.0\text{ V}}$

50. If a bridge rectifier diode opens, the output becomes a half-wave voltage, resulting in an increased ripple at 60 Hz.

51. $$V_{avg} = \frac{2V_p}{\pi} = \frac{2(115\text{ V})(1.414)}{\pi} \cong 104\text{ V}$$

The output of the bridge is correct. However, the 0 V output from the filter indicates that the **surge resistor is open** or that the **capacitor is shorted.**

52.
(a) Correct
(b) Incorrect. Open diode.
(c) Correct
(d) Incorrect. Open diode.

53. $$V_{sec} = \frac{120\text{ V}}{5} = 24\text{ V rms}$$

$$V_{p(sec)} = 1.414(24\text{ V}) = 33.9\text{ V}$$

The peak voltage for each half of the secondary is

$$\frac{V_{p(sec)}}{2} = \frac{33.9\text{ V}}{2} = 17\text{ V}$$

The peak inverse voltage for each diode is $\text{PIV} = 2(17\text{ V}) + 0.7\text{ V} = 34.7\text{ V}$

The peak current through each diode is

$$I_p = \frac{\frac{V_{p(sec)}}{2} - 0.7\text{ V}}{R_L} = \frac{17.0\text{ V} - 0.7\text{ V}}{330\ \Omega} = 49.4\text{ mA}$$

The diode ratings exceed the actual PIV and peak current.

The circuit should not fail.

Device Application Problems

54.
(a) Not plugged into ac outlet or no ac available at outlet. Check plug and/or breaker.
(b) Open transformer winding or open fuse. Check transformer and/or fuse.
(c) Incorrect transformer installed. Replace.
(d) Leaky filter capacitor. Replace.
(e) Rectifier faulty. Replace.
(f) Rectifier faulty. Replace.

55. The rectifier must be connected backwards.

56. -16 V with 60 Hz ripple

Advanced Problems

57. $V_r = \left(\frac{1}{fR_L C}\right)V_{p(in)}$

$C = \left(\frac{1}{fR_L V_r}\right)V_{p(in)} = \left(\frac{1}{(120\text{ Hz})(3.3\text{ k}\Omega)(0.5\text{ V})}\right)35\text{ V} = \mathbf{177\ \mu F}$

58. $V_{\mathrm{DC}} = \left(1 - \frac{1}{2fR_L C}\right)V_{p(in)}$

$\frac{V_{\mathrm{DC}}}{V_{p(in)}} = \left(1 - \frac{1}{2fR_L C}\right)$

$\frac{1}{2fR_L C} = 1 - \frac{V_{\mathrm{DC}}}{V_{p(in)}}$

$\frac{1}{2fR_L\left(1 - \frac{V_{\mathrm{DC}}}{V_{p(in)}}\right)} = C$

$C = \frac{1}{(240\text{ Hz})(1.0\text{ k}\Omega)(1 - 0.933)} = \frac{1}{(240\text{ Hz})(1.0\text{ k}\Omega)(0.067)} = 62.2\ \mu\text{F}$

Then

$V_r = \left(\frac{1}{fR_L C}\right)V_{p(in)} = \left(\frac{1}{(120\text{ Hz})(1.0\text{ k}\Omega)(62.2\ \mu\text{F})}\right)15\text{ V} = \mathbf{2\ V}$

59. The capacitor input voltage is

$V_{p(in)} = (1.414)(24\text{ V}) - 1.4\text{ V} = 32.5\text{ V}$

$R_{surge} = \frac{V_{p(in)}}{I_{surge}} = \frac{32.5\text{ V}}{50\text{ A}} = \mathbf{651\ m\Omega}$

The nearest standard value is 680 mΩ.

60. See Figure 2-14.

The voltage at point A with respect to ground is

$V_A = 1.414(9\text{ V}) = 12.7\text{ V}$

Therefore,

$V_B = 12.7\text{ V} - 0.7\text{ V} = 12\text{ V}$

$V_r = 0.05\,V_B = 0.05(12\text{ V}) = 0.6\text{ V}$ peak to peak

$C = \left(\frac{1}{fR_L V_r}\right)V_B = \left(\frac{1}{(120\text{ Hz})(680\ \Omega)(0.6\text{ V})}\right)12\text{ V} = 245\ \mu F$

The nearest standard value is $270\ \mu\text{F}$.

Let $R_{surge} = 1.0\ \Omega$.

$$I_{surge(max)} = \frac{12\text{ V}}{1.0\ \Omega} = 12\text{ A}$$

$$I_{\text{F(AV)}} = \frac{12\text{ V}}{680\ \Omega} = \mathbf{17.6\ mA}$$

$$PIV = 2\,V_{p(out)} + 0.7\text{ V} = \mathbf{24.7\ V}$$

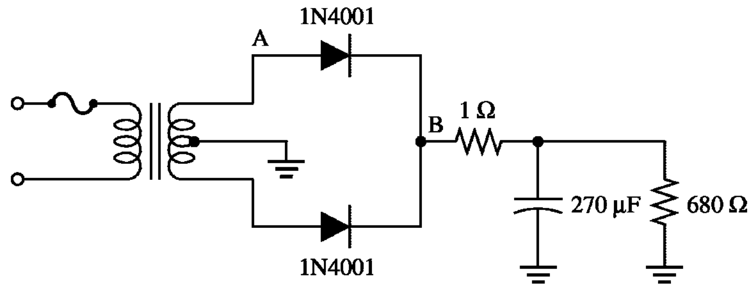

Figure 2-14

61. See Figure 2-15.

$$I_{L(max)} = 100\text{ mA}$$

$$R_L = \frac{9\text{ V}}{100\text{ mA}} = 90\ \Omega$$

$$V_r = 1.414(0.25\text{ V}) = 0.354\text{ V}$$

$$V_r = 2(0.35\text{ V}) = 0.71\text{ V peak to peak}$$

$$V_r = \left(\frac{1}{(120\text{ Hz})(90\ \Omega)C}\right)9\text{ V}$$

$$C = \frac{9\text{ V}}{(120\text{ Hz})(90\ \Omega)(0.71\text{ V})} = 1174\ \mu\text{F}$$

Use $C = 1200\ \mu\text{F}$.

Each half of the supply uses identical components. 1N4001 diodes are feasible since the average current is $(0.318)(100\text{ mA}) = 31.8\text{ mA}$.

$R_{surge} = 1.0\ \Omega$ will limit the surge current to an acceptable value.

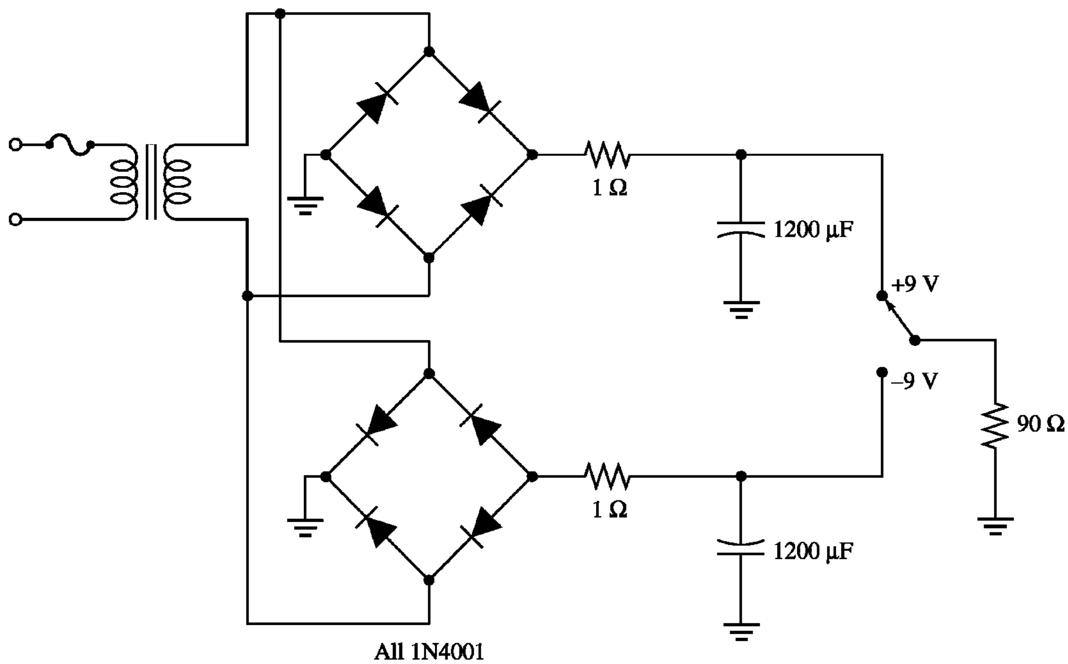

Figure 2-15

62. See Figure 2-16.

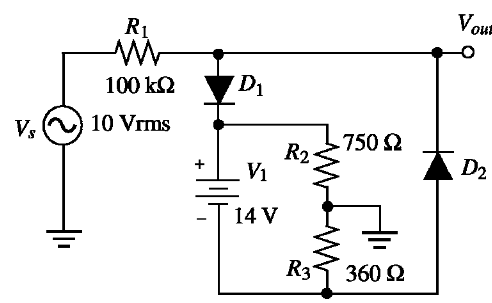

Figure 2-16

63. $V_{C1} = (1.414)(120\text{ V}) - 0.7\text{ V} = \mathbf{170\ V}$

$V_{C2} = 2(1.414)(120\text{ V}) - 2(0.7\text{ V}) = \mathbf{338\ V}$

Chapter 2

Multisim Troubleshooting Problems

64. Diode shorted

65. Diode open

66. Diode open

67. Diode shorted

68. No fault

69. Diode shorted

70. Diode leaky

71. Diode open

72. Diode shorted

73. Diode shorted

74. Diode leaky

75. Diode open

76. Bottom diode open

77. Reduced transformer turns ratio

78. Open filter capacitor

79. Diode leaky

80. D_1 open

81. Load resistor open

Chapter 3
Special-Purpose Diodes

Section 3-1 The Zener Diode

1. See Figure 3-1.

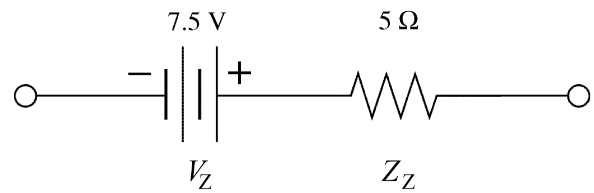

Figure 3-1

2. $I_{ZK} \cong \mathbf{3\ mA}$
$V_Z \cong \mathbf{-9\ V}$

3. $$Z_Z = \frac{\Delta V_Z}{\Delta I_Z} = \frac{5.65\ \text{V} - 5.6\ \text{V}}{30\ \text{mA} - 20\ \text{mA}} = \frac{0.05\ \text{V}}{10\ \text{mA}} = \mathbf{5\ \Omega}$$

4. $\Delta I_Z = 50\ \text{mA} - 25\ \text{mA} = 25\ \text{mA}$

$\Delta V_Z = \Delta I_Z Z_Z = (+25\ \text{mA})(15\ \Omega) = +0.375\ \text{V}$

$V_Z = V_Z + \Delta V_Z = 4.7\ \text{V} + 0.375\ \text{V} = \mathbf{5.08\ V}$

5. $\Delta T = 70°\text{C} - 25°\text{C} = 45°\text{C}$

$$V_Z = 6.8\ \text{V} + \frac{(6.8\ \text{V})(0.0004/°\text{C})}{45°\text{C}} = 6.8\ \text{C} + 0.12\ \text{V} = \mathbf{6.92\ V}$$

6. $5\ \text{W} - 5.3\ \text{mW}/°\ \text{C}(100°\ \text{C} - 25°\ \text{C}) = 4.60\ \text{W}.$

7. From the data sheet

(a) Nominal zener voltage $= 36\ \text{V}$

(b) Maximum zener voltage $= 37.8\ \text{V}$

(c) Knee current IZK $= 0.25\ \text{mA}$

(d) Derating factor $= 6.67\ \text{mW}/°\ \text{C}$

(e) Temperature above which derating applies $= 50°\ \text{C}$

Chapter 3

Section 3-2 Zener Diode Applications

8. $V_{\text{IN(min)}} = V_\text{Z} + I_\text{ZK}R = 14\text{ V} + (1.5\text{ mA})(560\ \Omega) = \mathbf{14.8\ V}$

9. $\Delta V_\text{Z} = (I_\text{Z} - I_\text{ZK})Z_\text{Z} = (28.5\text{ mA})(20\ \Omega) = 0.57\text{ V}$

$V_\text{OUT} = V_\text{Z} - \Delta V_\text{Z} = 14\text{ V} - 0.57\text{ V} = 13.43\text{ V}$

$V_{\text{IN(min)}} = I_\text{ZK}R + V_\text{OUT} = (1.5\text{ mA})(560\ \Omega) + 13.43\text{ V} = \mathbf{14.3\ V}$

10. $\Delta V_\text{Z} = I_\text{Z}Z_\text{Z} = (40\text{ mA} - 30\text{ mA})(30\ \Omega) = 0.3\text{ V}$

$V_\text{Z} = 12\text{ V} + \Delta V_\text{Z} = 12\text{ V} + 0.3\text{ V} = 12.3\text{ V}$

$$R = \frac{V_\text{IN} - V_\text{Z}}{40\text{ mA}} = \frac{18\text{ V} - 12.3\text{ V}}{40\text{ mA}} = \mathbf{143\ \Omega}$$

11. $V_\text{Z} \cong 12\text{ V} + 0.3\text{ V} = 12.3\text{ V}$

See Figure 3-2.

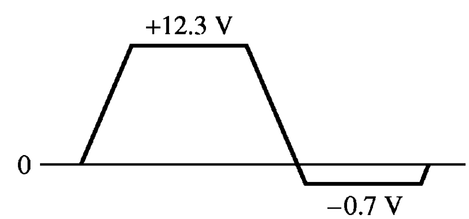

Figure 3-2

12. $V_{\text{Z(min)}} = V_\text{Z} - \Delta I_\text{Z}Z_\text{Z} = 5.1\text{ V} - (49\text{ mA} - 1\text{ mA})(7\ \Omega)$
$= 5.1\text{ V} - (48\text{ mA})(7\ \Omega) = 5.1\text{ V} - 0.336\text{ V} = 4.76\text{ V}$

$V_\text{R} = 8\text{ V} - 4.76\text{ V} = 3.24\text{ V}$

$$I_\text{T} = \frac{V_\text{R}}{R} = \frac{3.24\text{ V}}{22\ \Omega} = 147\text{ mA}$$

$I_{\text{L(max)}} = 147\text{ mA} - 1\text{ mA} = \mathbf{146\ mA}$

$V_{\text{Z(max)}} = 5.1\text{ V} + (70\text{ mA} - 49\text{ mA})(7\ \Omega) = 5.1\text{ V} + 147\text{ mV} = 5.25\text{ V}$

$V_\text{R} = 8\text{ V} - 5.25\text{ V} = 2.75\text{ V}$

$$I_\text{T} = \frac{2.75\text{ V}}{22\ \Omega} = 125\text{ mA}$$

$I_{\text{L(min)}} = 125\text{ mA} - 70\text{ mA} = \mathbf{55\ mA}$

13. $\%\ \text{Load regulation} = \dfrac{V_{Z(\max)} - V_{Z(\min)}}{V_{Z(\min)}} \times 100\% = \dfrac{5.25\ \text{V} - 4.76\ \text{V}}{4.76\ \text{V}} \times 100\% = \mathbf{10.3\%}$

14. With no load and $V_{IN} = 6$ V:

$$I_Z \cong \frac{V_{IN} - V_Z}{R + Z_Z} = \frac{6\ \text{V} - 5.1\ \text{V}}{29\ \Omega} = 31\ \text{mA}$$

$$V_{OUT} = V_Z - \Delta I_Z Z_Z = 5.1\ \text{V} - (49\ \text{mA} - 31\ \text{mA})(7\ \Omega) = 5.1\ \text{V} - 0.126\ \text{V} = 4.97\ \text{V}$$

With no load and $V_{IN} = 12$ V:

$$I_Z \cong \frac{V_{IN} - V_Z}{R + Z_Z} = \frac{12\ \text{V} - 5.1\ \text{V}}{29\ \Omega} = 238\ \text{mA}$$

$$V_{OUT} = V_Z + \Delta I_Z Z_Z = 5.1\ \text{V} + (238\ \text{mA} - 49\ \text{mA})(7\ \Omega) = 5.1\ \text{V} + 1.32\ \text{V} = 6.42\ \text{V}$$

$$\%\ \text{Line regulation} = \frac{\Delta V_{OUT}}{\Delta V_{IN}} \times 100\% = \frac{6.42\ \text{V} - 4.97\ \text{V}}{12\ \text{V} - 6\ \text{V}} \times 100\% = \mathbf{24.2\%}$$

15. $\%\ \text{Load regulation} = \dfrac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% = \dfrac{8.23\ \text{V} - 7.98\ \text{V}}{7.98\ \text{V}} \times 100\% = \mathbf{3.13\%}$

16. $\%\ \text{Line regulation} = \dfrac{\Delta V_{OUT}}{\Delta V_{IN}} \times 100\% = \dfrac{0.2\ \text{V}}{10\ \text{V} - 5\ \text{V}} \times 100\% = \mathbf{4\%}$

17. $\%\ \text{Load regulation} = \dfrac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% = \dfrac{3.6\ \text{V} - 3.4\ \text{V}}{3.4\ \text{V}} \times 100\% = \mathbf{5.88\%}$

Section 3-3 The Varactor Diode

18. At 5 V, $C = 20$ pF

At 20 V, $C = 10$ pF

$\Delta C = 20\ \text{pF} - 10\ \text{pF} = \mathbf{10\ pF}$ (decrease)

19. From the graph, $V_R = \mathbf{3\ V}$ @ 25 pF

20. $$f_r = \frac{1}{2\pi\sqrt{LC_T}}$$

$$C_T = \frac{1}{4\pi^2 L f_r^2} = \frac{1}{4\pi^2 (2\ \text{mH})(1\ \text{MHz})^2} = 12.7\ \text{pF}$$

Since they are in series, each varactor must have a capacitance of $2C_T = \mathbf{25.4\ pF}$

21. Each varactor has a capacitance of 25.4 pF. Therefore, from the graph, V_R must be slightly less than 3 V.

Section 3-4 Optical Diodes

22. $I_F = \dfrac{24\text{ V}}{680\ \Omega} = 35.3\text{ mA}$

From the graph, the radiant power is approximately **80 mW**.

23. See Figure 3-3.

$R = \dfrac{5\text{ V} - 2.1\text{ V}}{30\text{ mA}} = 97\ \Omega$

The nearest standard 1% value is $97.6\ \Omega$ or the nearest standard 5% value is $91\ \Omega$.

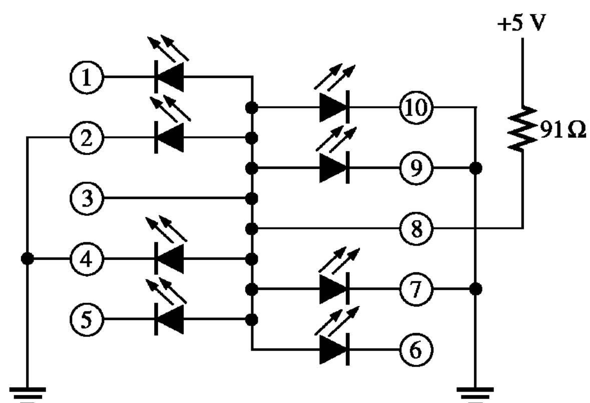

Figure 3-3

24. $V_F \cong 2.2\text{ V}$ for $I_F = 20\text{ mA}$

Maximum LEDs/branch $= \dfrac{9\text{ V}}{2.2\text{ V}} \cong 4$

Select 3 LEDs/branch:

Number of branches $= \dfrac{48}{3} = 16$

$R_{LIMIT} = \dfrac{9\text{ V} - 3(2.2\text{ V})}{20\text{ mA}} = 120\ \Omega$

Use sixteen $120\ \Omega$ resistors.

25. $V_F \cong 2.5\text{ V}$ for $I_F = 30\text{ mA}$

Maximum LEDs/branch $= \dfrac{24\text{ V}}{2.5\text{ V}} \cong 9.6$

Select 5 LEDs/branch:

Number of branches $= \dfrac{100}{5} = 20$

$R_{LIMIT} = \dfrac{24\text{ V} - 5(2.5\text{ V})}{30\text{ mA}} = 383\ \Omega$

See Figure 3-4.

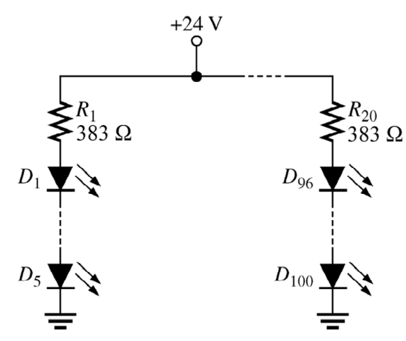

Figure 3-4

26. $I_R = \dfrac{10\text{ V}}{200\text{ k}\Omega} = \mathbf{50\ \mu A}$

27. (a) $R = \dfrac{V_S}{I} = \dfrac{3\text{ V}}{100\ \mu\text{A}} = \mathbf{30\ k\Omega}$

(b) $R = \dfrac{V_S}{I} = \dfrac{3\text{ V}}{350\ \mu\text{A}} = \mathbf{8.57\ k\Omega}$

(c) $R = \dfrac{V_S}{I} = \dfrac{3\text{ V}}{510\ \mu\text{A}} = \mathbf{5.88\ k\Omega}$

28. The microammeter reading will increase.

Section 3-5 The Solar Cell

29. The parts of a solar cell are *p* region, *n* region, conductive grid, conductive bottom layer, and reflective coating.

30. Number of series connected cells $= \dfrac{V_{out}}{V_{cell}} = \dfrac{15\text{ V}}{0.5\text{ V}} = 30$

31. $I = \dfrac{V_{out}}{R_L} = \dfrac{15\text{ V}}{10\text{ k}\Omega} = 1.5\text{ mA}$

32. Connect seven $\left(\dfrac{10\text{ mA}}{1} \cdot t\text{ mA} = 6.67\right)$ of the 30-cell series connections in parallel.

$I_{TOT} = 7(1.5\text{ mA}) = 10.5\text{ mA}$

Section 3-6 Other Types of Diodes

33. $R = \dfrac{\Delta V}{\Delta I} = \dfrac{125\text{ mV} - 200\text{ mV}}{0.25\text{ mA} - 0.15\text{ mA}} = \dfrac{-75\text{ mV}}{0.10\text{ mA}} = \mathbf{-750\ \Omega}$

34. Tunnel diodes are used in oscillators.

35. The reflective ends cause the light to bounce back and forth, thus increasing the intensity of the light. The partially reflective end allows a portion of the reflected light to be emitted.

Section 3-7 Troubleshooting

36. (a) All voltages are correct.

(b) V_3 should be 12 V. Zener is open.

(c) V_1 should be 120 V. Fuse is open.

(d) Capacitor C_1 is open.

(e) R is open or D_5 is shorted.

37. (a) With D_5 open, $V_{\text{OUT}} \cong \mathbf{30\ V}$.

(b) With R open, $V_{\text{OUT}} = \mathbf{0\ V}$.

(c) With C leaky, V_{OUT} has excessive **120 Hz ripple limited to 12 V**.

(d) With C open, V_{OUT} is **full wave rectified voltage limited to 12 V**.

(e) With D_3 open, V_{OUT} has **60 Hz ripple limited to 12 V**.

(f) With D_2 open, V_{OUT} has **60 Hz ripple limited to 12 V**.

(g) With T open, $V_{\text{OUT}} = \mathbf{0\ V}$.

(h) With F open, $V_{\text{OUT}} = \mathbf{0\ V}$.

Device Application Problems

38. (a) Faulty regulator

39. Incorrect transformer secondary voltage

40. LED open, limiting resistor open, faulty regulator, faulty bridge rectifier

41. $I_{\text{L}} = \dfrac{12\text{ V}}{1\text{ k}\Omega} = 12\text{ mA}$; $V_{\text{reg}} = 16\text{ V} - 12\text{ V} = 4\text{ V}$

$P_{\text{reg}} = (4\text{ V})(12\text{ mA}) = \mathbf{48\ mW}$

Datasheet Problems

42. From the datasheet of textbook Figure 3-7:

(a) @ 25°C: $P_{\text{D(max)}} = \mathbf{1.0\ W}$ for a 1N4738A

(b) For a 1N4751A:

@ 70°C; $P_{\text{D(max)}} = 1.0\text{ W} - (6.67\text{ mW/°C})(20\text{°C}) = 1.0\text{ W} - 133\text{ mW} = \mathbf{867\ mW}$
@ 100°C; $P_{\text{D(max)}} = 1.0\text{ W} - (6.67\text{ mW/°C})(50\text{°C}) = 1.0\text{ W} - 333\text{ mW} = \mathbf{667\ mW}$

(c) $I_{\text{ZK}} = \mathbf{0.5\ mA}$ for a 1N4738A

(d) @ 25°C: $I_{\text{ZM}} = 1\text{ W}/27\text{ V} = \mathbf{37.0\ mA}$ for a 1N4750A

(e) $\Delta Z_{\text{Z}} = 700\ \Omega - 7.0\ \Omega = \mathbf{693\ \Omega}$ for a 1N4740A

43. From the graph of textbook Figure 3-24:

(a) $C_{\text{MAX}} = 60\text{ pF}$

(b) $C_{\text{MIN}} = 20\text{ pF}$

(c) $CR = \dfrac{C_{\text{MAX}}}{C_{\text{MIN}}} = \dfrac{60\text{ pF}}{20\text{ pF}} = 3$

44. From the datasheet of textbook 3-34:

(a) 9 V cannot be applied in reverse across a TSMF1000 because $V_{\text{R(max)}} = 5\text{ V}$.

(b) When 5.1 V is used to forward-bias the TSMF1000 for $I_{\text{F}} = 20\text{ mA}$, $V_{\text{F}} \cong 1.3\text{ V}$

$$R = \frac{5.1\text{ V} - 1.3\text{ V}}{20\text{ mA}} = \frac{3.8\text{ V}}{20\text{ mA}} = \mathbf{190\ \Omega}$$

(c) At $25°\text{C}$ maximum power dissipation is 190 mW.

If $V_{\text{F}} = 1.5\text{ V}$ and $I_{\text{F}} = 50\text{ mA}$, $P_D = 75\text{ mW}$. The power rating is **not exceeded.**

(d) For $I_{\text{F}} = 40\text{ mA}$, radiant intensity is approximately **0.9 mW/sr**.

(e) For $I_{\text{F}} = 100\text{ mA}$, and $\theta = 20°$, radiant intensity is 40% of maximum or $(0.4)(25\text{ mW/sr}) = \mathbf{10\ mW/sr}$

45. From the datasheet of textbook Figure 3-47:

(a) With no incident light and a $10\text{ k}\Omega$ series resistor, the typical voltage across the resistor is approximately $V_{\text{R}} = (1\text{ nA})(1\text{ k}\Omega) = \mathbf{1\ \mu V}$.

(b) Reverse current is greatest at about **940 nm**.

(c) Sensitivity is maximum for $\lambda \cong \mathbf{830\ nm}$.

Advanced Problems

46. See Figure 3-5.

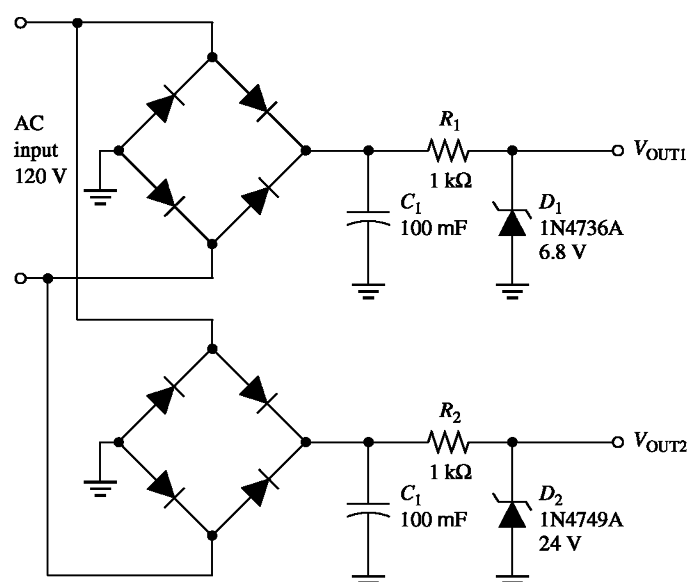

Figure 3-5

47. $V_{\text{OUT(1)}} \cong \mathbf{6.8\ V}$, $V_{\text{OUT(2)}} \cong \mathbf{24\ V}$

48. For a 10 kΩ load on each output:

$$I_{\text{OUT(1)}} = \frac{V_{\text{OUT1}}}{R_1} \cong \frac{6.8\text{ V}}{10\text{ k}\Omega} = 0.68\text{ mA}$$
$$I_{\text{OUT(2)}} = \frac{V_{\text{OUT2}}}{R_2} \cong \frac{24\text{ V}}{10\text{ k}\Omega} = 2.4\text{ mA}$$
$$V_{\text{R1}} \cong 120\text{ V} - 6.8\text{ V} = 113.2\text{ V}$$
$$I_{\text{Z1}} = \frac{113.2\text{ V}}{1\text{ k}\Omega} - 0.68\text{ mA} = 112.5\text{ mA}$$
$$V_{\text{R2}} \cong 120\text{ V} - 24\text{ V} = 96\text{ V}$$
$$I_{\text{Z2}} = \frac{96\text{ V}}{1\text{ k}\Omega} - 2.4\text{ mA} = 93.6\text{ mA}$$
$$I_{\text{T}} = 0.68\text{ mA} + 2.4\text{ mA} + 112.5\text{ mA} + 93.6\text{ mA} = 209.2\text{ mA}$$

The fuse rating should be 250 mA or **1/4 A**.

49. See Figure 3-6.

Use a IN4738A zener.

$$I_{\text{T}} = 35\text{ mA} + 31\text{ mA} = 66\text{ mA}$$
$$R = \frac{24\text{ V} - 8.2\text{ V}}{66\text{ mA}} = 239\ \Omega$$

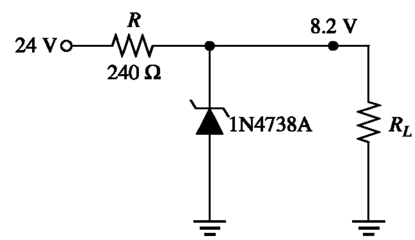

Figure 3-6

50.
$$C_{\max} = \frac{1}{4\pi^2 L f_{\min}^2} = \frac{1}{4\pi^2(2\text{ mH})(350\text{ kHz})^2} = 103.4\text{ pF}$$
$$C_{\min} = \frac{1}{4\pi^2 L f_{\max}^2} = \frac{1}{4\pi^2(2\text{ mH})(850\text{ kHz})^2} = 17.5\text{ pF}$$

To achieve this capacitance range, use an 826A varactor and change V_2 to 30 V.

51. See Figure 3-7. From datasheet, $V_{\text{F}} = 2.1\text{ V}$ for red LED.

$$R = \frac{V_{\text{D}}}{I} = \frac{12\text{ V} - 2.1\text{ V}}{20\text{ mA}} = 495\ \Omega$$

Use standard value of 510 Ω.

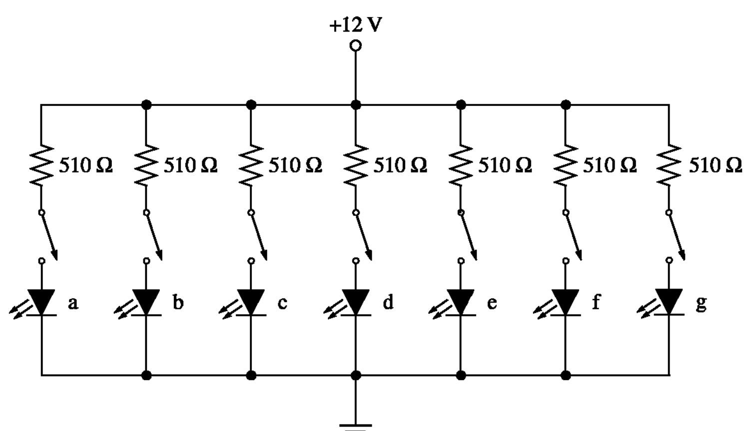

Figure 3-7

52. See Figure 3-8.

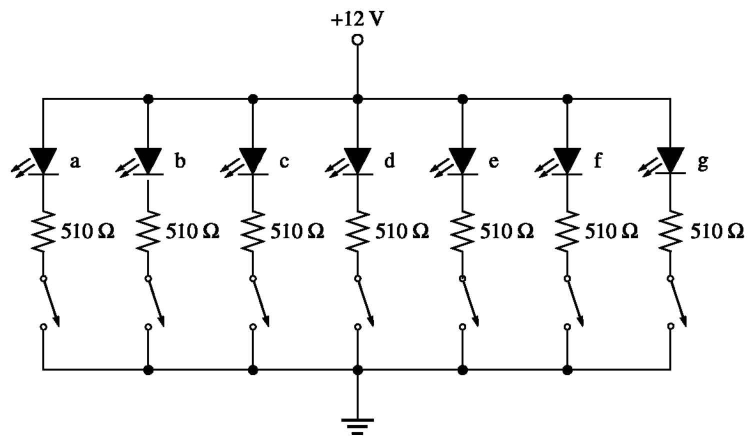

Figure 3-8

Multisim Troubleshooting Problems

53. Zener diode open

54. Capacitor open

55. Zener diode shorted

56. Resistor open

Chapter 4
Bipolar Junction Transistors

Section 4-1 Bipolar Junction Transistor (BJT) Structure

1. *npn* has an *n*-type emitter and collector and a *p*-type base. The *pnp* has a *p*-type emitter and emitter and an *n*-type base.

2. The term **bipolar** refers to the use of both holes and electrons as current carriers in the transistor structure

3. Majority carriers in the base region of an *npn* transistor are **holes**.

4. Because of the narrow base region, the minority carriers invading the base region find a limited number of partners for recombination and, therefore, move across the junction into the collector region rather than out of the base lead.

Section 4-2 Basic BJT Operation

5. The base is narrow and lightly doped so that a small recombination (base) current is generated compared to the collector current.

6. $I_{\mathrm{B}} = 0.02 I_{\mathrm{E}} = 0.02(30\text{ mA}) = 0.6\text{ mA}$

$I_{\mathrm{C}} = I_{\mathrm{E}} - I_{\mathrm{B}} = 30\text{ mA} - 0.6\text{ mA} = \mathbf{29.4\ mA}$

7. The base must be negative with respect to the collector and positive with respect to the emitter.

8. $I_{\mathrm{C}} = I_{\mathrm{E}} - I_{\mathrm{B}} = 5.34\text{ mA} - 475\ \mu\text{A} = \mathbf{4.87\ mA}$

Section 4-3 BJT Characteristics and Parameters

9. $$\alpha_{\mathrm{DC}} = \frac{I_{\mathrm{C}}}{I_{\mathrm{E}}} = \frac{8.23\text{ mA}}{8.69\text{ mA}} = \mathbf{0.947}$$

10. $$\beta_{\mathrm{DC}} = \frac{I_{\mathrm{C}}}{I_{\mathrm{B}}} = \frac{25\text{ mA}}{200\ \mu\text{A}} = \mathbf{125}$$

11. $I_{\mathrm{B}} = I_{\mathrm{E}} - I_{\mathrm{C}} = 20.5\text{ mA} - 20.3\text{ mA} = 0.2\text{ mA} = 200\ \mu\text{A}$

$$\beta_{\mathrm{DC}} = \frac{I_{\mathrm{C}}}{I_{\mathrm{B}}} = \frac{20.3\text{ mA}}{200\ \mu\text{A}} = \mathbf{101.5}$$

12. $I_E = I_C + I_B = 5.35\text{ mA} + 50\ \mu\text{A} = 5.40\text{ mA}$

$$\alpha_{DC} = \frac{I_C}{I_E} = \frac{5.35\text{ mA}}{5.40\text{ mA}} = \mathbf{0.99}$$

13. $I_C = \alpha_{DC} I_E = 0.96(9.35\text{ mA}) = \mathbf{8.98\ mA}$

14. $$I_C = \frac{V_{R_C}}{R_C} = \frac{5\text{ V}}{1.0\text{ k}\Omega} = 5\text{ mA}$$

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{5\text{ mA}}{50\ \mu\text{A}} = \mathbf{100}$$

15. $$\alpha_{DC} = \frac{\beta_{DC}}{\beta_{DC}+1} = \frac{100}{101} = \mathbf{0.99}$$

16. $$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3\text{ V} - 0.7\text{ V}}{101\text{ k}\Omega} = \mathbf{23\ \mu A}$$

$I_C = \beta_{DC} I_B = 200(23\ \mu\text{A}) = \mathbf{4.6\ mA}$

$I_E = I_C + I_B = 4.6\text{ mA} + 23\ \mu\text{A} = \mathbf{4.62\ mA}$

$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (4.6\text{ mA})(1.0\text{ k}\Omega) = \mathbf{5.4\ V}$

17. $I_C =$ does not change.

For $V_{CC} = 10$ V:
$V_{CE} = V_{CC} = I_C R_C = 10\text{ V} - (4.6\text{ mA})(1.0\text{ k}\Omega) = 5.4\text{ V}$
For $V_{CC} = 15$ V:
$V_{CE} = 15\text{ V} - (4.6\text{ mA})(1.0\text{ k}\Omega) = 10.7\text{ V}$
$\Delta V_{CE} = 10.7\text{ V} - 5.4\text{ V} = \mathbf{5.3\ V}$ increase

18. $$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{4\text{ V} - 0.7\text{ V}}{4.7\text{ k}\Omega} = \frac{3.3\text{ V}}{4.7\text{ k}\Omega} = \mathbf{702\ \mu A}$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{24\text{ V} - 8\text{ V}}{470\ \Omega} = \mathbf{34\ mA}$$

$I_E = I_C + I_B = 34\text{ mA} + 702\ \mu\text{A} = \mathbf{34.7\ mA}$

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{34\text{ mA}}{702\ \mu\text{A}} = \mathbf{48.4}$$

19. (a) $V_{BE} = \mathbf{0.7\ V}$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{4.3\ \text{V}}{3.9\ \text{k}\Omega} = 1.1\ \text{mA}$$
$$I_C = \beta_{DC} I_B = 50(1.1\ \text{mA}) = 55\ \text{mA}$$
$$V_{CE} = V_{CC} - I_C R_C = 15\ \text{V} - (55\ \text{mA})(180\ \Omega) = \mathbf{5.10\ V}$$
$$V_{CB} = V_{CE} - V_{BE} = 5.10\ \text{V} - 0.7\ \text{V} = \mathbf{4.40\ V}$$

(b) $V_{BE} = \mathbf{-0.7\ V}$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{-3\ \text{V} - (-0.7\ \text{V})}{27\ \text{k}\Omega} = \frac{-2.3\ \text{V}}{27\ \text{k}\Omega} = -85.2\ \mu\text{A}$$
$$I_C = \beta_{DC} I_B = 125(-85.2\ \mu\text{A}) = -10.7\ \text{mA}$$
$$V_{CE} = V_{CC} - I_C R_C = -8\ \text{V} - (-10.7\ \text{mA})(390\ \Omega) = \mathbf{-3.83\ V}$$
$$V_{CB} = V_{CE} - V_{BE} = -3.83\ \text{V} - (-0.7\ \text{V}) = \mathbf{-3.13\ V}$$

20. (a) $I_{C(sat)} = \dfrac{V_{CC}}{R_C} = \dfrac{15\ \text{V}}{180\ \Omega} = 83.3\ \text{mA}$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\ \text{V} - 0.7\ \text{V}}{3.9\ \text{k}\Omega} = 1.1\ \text{mA}$$
$$I_C = \beta_{DC} I_B = 50(1.1\ \text{mA}) = 55\ \text{mA}$$
$$I_C < I_{C(sat)}$$

Therefore, the transistor is **not saturated**.

(b) $I_{C(sat)} = \dfrac{V_{CC}}{R_C} = \dfrac{8\ \text{V}}{390\ \Omega} = 20.5\ \text{mA}$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3\ \text{V} - 0.7\ \text{V}}{27\ \text{k}\Omega} = 85.2\ \mu\text{A}$$
$$I_C = \beta_{DC} I_B = 125(85.2\ \mu\text{A}) = 10.7\ \text{mA}$$
$$I_C < I_{C(sat)}$$

Therefore, the transistor is **not saturated**.

21. $V_B = 2\ \text{V}$

$$V_E = V_B - V_{BE} = 2\ \text{V} - 0.7\ \text{V} = 1.3\ \text{V}$$
$$I_E = \frac{V_E}{R_E} = \frac{1.3\ \text{V}}{1.0\ \text{k}\Omega} = \mathbf{1.3\ mA}$$
$$I_C = \alpha_{DC} I_E = (0.98)(1.3\ \text{mA}) = \mathbf{1.27\ mA}$$
$$\beta_{DC} = \frac{\alpha_{DC}}{1 - \alpha_{DC}} = \frac{0.98}{1 - 0.98} = 49$$
$$I_B = I_E - I_C = 1.3\ \text{mA} - 1.27\ \text{mA} = \mathbf{30\ \mu A}$$

22. (a) $V_{\text{B}} = V_{\text{BB}} = \mathbf{10\ V}$

$V_{\text{C}} = V_{\text{CC}} = \mathbf{20\ V}$
$V_{\text{E}} = V_{\text{B}} - V_{\text{BE}} = 10\text{ V} - 0.7\text{ V} = \mathbf{9.3\ V}$
$V_{\text{CE}} = V_{\text{C}} - V_{\text{E}} = 20\text{ V} - 9.3\text{ V} = \mathbf{10.7\ V}$
$V_{\text{BE}} = \mathbf{0.7\ V}$
$V_{\text{CB}} = V_{\text{C}} - V_{\text{B}} = 20\text{ V} - 10\text{ V} = \mathbf{10\ V}$

(b) $V_{\text{B}} = V_{\text{BB}} = \mathbf{-4\ V}$

$V_{\text{C}} = V_{\text{CC}} = \mathbf{-12\ V}$
$V_{\text{E}} = V_{\text{B}} - V_{\text{BE}} = -4\text{ V} - (-0.7\text{ V}) = \mathbf{-3.3\ V}$
$V_{\text{CE}} = V_{\text{C}} - V_{\text{E}} = -12\text{ V} - (-3.3)\text{ V} = \mathbf{-8.7\ V}$
$V_{\text{BE}} = \mathbf{-0.7\ V}$
$V_{\text{CB}} = V_{\text{C}} - V_{\text{B}} = -12\text{ V} - (-4\text{ V}) = \mathbf{-8\ V}$

23. For $\beta_{\text{DC}} = 100$:

$$I_{\text{E}} = \frac{V_{\text{B}} - V_{\text{BE}}}{R_{\text{E}}} = \frac{10\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = 930\ \mu\text{A}$$
$$\alpha_{\text{DC}} = \frac{\beta_{\text{DC}}}{1 + \beta_{\text{DC}}} = \frac{100}{101} = 0.990$$
$$I_{\text{C}} = \alpha_{\text{DC}} I_{\text{E}} = (0.990)(930\ \mu\text{A}) = 921\ \mu\text{A}$$

For $\beta_{\text{DC}} = 150$:
$I_{\text{E}} = 930\ \mu\text{A}$
$$\alpha_{\text{DC}} = \frac{\beta_{\text{DC}}}{1 + \beta_{\text{DC}}} = \frac{150}{151} = 0.993$$
$$I_{\text{C}} = \alpha_{\text{DC}} I_{\text{E}} = (0.993)(930\ \mu\text{A}) = 924\ \mu\text{A}$$
$$\Delta I_{\text{C}} = 924\ \mu\text{A} - 0.921\ \mu\text{A} = \mathbf{3\ \mu A}$$

24. $P_{\text{D(max)}} = V_{\text{CE}} I_{\text{C}}$

$$V_{\text{CE(max)}} = \frac{P_{\text{D(max)}}}{I_{\text{C}}} = \frac{1.2\text{ W}}{50\text{ mA}} = \mathbf{24\ V}$$

25. $P_{\text{D(max)}} = 0.5\text{ W} - (75°\text{C})(1\text{ mW/°C}) = 0.5\text{ W} - 75\text{ mW} = \mathbf{425\ mW}$

Section 4-4 The BJT as an Amplifier

26. $V_{out} = A_v V_{in} = 50(100\text{ mV}) = \mathbf{5\ V}$

27. $$A_v = \frac{V_{out}}{V_{in}} = \frac{100\text{ V}}{300\text{ mV}} = \mathbf{33.3}$$

28. $A_v = \dfrac{R_C}{r'_e} = \dfrac{560\ \Omega}{10\ \Omega} = 56$

$V_c = V_{out} = A_v V_{in} = 56(50\text{ mV}) = \mathbf{2.8\ V}$

29. $I_B = \dfrac{V_{BB} - V_{BE}}{R_B} = \dfrac{2.5\text{ V} - 0.7\text{ V}}{100\text{ k}\Omega} = 18\ \mu\text{A}$

$I_C = \beta_{DC} I_B = 250(18\ \mu\text{A}) = 4.5\text{ mA}$

$R_C = \dfrac{V_{CC} - V_{CE}}{I_C} = \dfrac{9\text{ V} - 4\text{ V}}{4.5\text{ mA}} = \mathbf{1.1\ k\Omega}$

30. (a) DC current gain $= \beta_{DC} = \mathbf{50}$

(b) DC current gain $= \beta_{DC} = \mathbf{125}$

Section 4-5 The BJT as a Switch

31. $I_{C(sat)} = \dfrac{V_{CC}}{R_C} = \dfrac{5\text{ V}}{10\text{ k}\Omega} = \mathbf{500\ \mu A}$

$I_{B(min)} = \dfrac{I_{C(sat)}}{\beta_{DC}} = \dfrac{500\ \mu\text{A}}{150} = \mathbf{3.33\ \mu A}$

$I_{B(min)} = \dfrac{V_{IN(min)} - 0.7\text{ V}}{R_B}$

$R_B I_{B(min)} = V_{IN(min)} - 0.7\text{ V}$

$V_{IN(min)} = R_B I_{B(min)} + 0.7\text{ V} = (3.33\ \mu\text{A})(1.0\text{ M}\Omega) + 0.7\text{ V} = \mathbf{4.03\ V}$

32. $I_{C(sat)} = \dfrac{15\text{ V}}{1.2\text{ k}\Omega} = 12.5\text{ mA}$

$I_{B(min)} = \dfrac{I_{C(sat)}}{\beta_{DC}} = \dfrac{12.5\text{ mA}}{50} = 250\ \mu\text{A}$

$R_{B(min)} = \dfrac{V_{IN} - 0.7\text{ V}}{I_{B(min)}} = \dfrac{4.3\text{ V}}{250\ \mu\text{A}} = \mathbf{17.2\ k\Omega}$

$V_{IN(cutoff)} = \mathbf{0\ V}$

33. Assume $V_{CE(sat)} = 0\text{ V}$

$I_{C(sat0)} = \dfrac{V_{CC}}{R_C} = \dfrac{5\text{ V}}{10\text{ k}\Omega} = 0.5\text{ mA}$

$I_B = \dfrac{I_{C(sat)}}{\beta_{DC}} = \dfrac{0.5\text{ mA}}{100} = 5\text{ mA}$

$V_{INPUT} = I_B R_B + 0.7\text{ V} = 0.75\text{ V} + 0.7\text{ V} = 1.45\text{ V}$

34. $V_{\text{INPUT}} = 0.3\text{ V}$ is insufficient to forward bias the base-emitter junctions and turn either transistor on, therefore the output voltage is equal to V_{CC}.

Section 4-6 The Phototransistor

35. $I_{\text{C}} = \beta_{\text{DC}} I_{\lambda} = (200)(100\ \mu\text{A}) = \mathbf{20\ mA}$

36. $I_{\lambda} = (50\text{ lm/m}^2)(1\ \mu\text{A/lm/m}^2) = 50\ \mu\text{A}$

$I_{\text{E}} = \beta_{\text{DC}} I_{\lambda} = (100)(50\ \mu\text{A}) = \mathbf{5\ mA}$

37. $I_{out} = (0.30)(100\text{ mA}) = \mathbf{30\ mA}$

38. $\dfrac{I_{\text{OUT}}}{I_{\text{IN}}} = 0.6$

$$I_{\text{IN}} = \frac{I_{\text{OUT}}}{0.6} = \frac{10\text{ mA}}{0.6} = \mathbf{16.7\ mA}$$

Section 4-7 Transistor Categories and Packaging

39. See Figure 4-1.

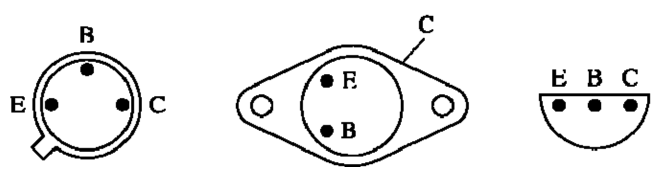

Figure 4-1

40.
(a) Small-signal
(b) Power
(c) Power
(d) Small-signal
(e) RF

Section 4-8 Troubleshooting

41. With the positive probe on the emitter and the negative probe on the base, the ohmmeter indicates an **open**, since this reverse-biases the base-emitter junction. With the positive probe on the base and the negative probe on the emitter, the ohmmeter indicates a **very low resistance**, since this forward-biases the base-collector junction.

42. (a) Transistor's collector junction or terminal is open.

(b) Collector resistor is open.

(c) Operating properly.

(d) Transistor's base junction or terminal open (no base or collector current).

43. (a) $I_B = \dfrac{5\text{ V} - 0.7\text{ V}}{68\text{ k}\Omega} = 63.2\ \mu\text{A}$

$I_C = \dfrac{9\text{ V} - 3.2\text{ V}}{3.3\text{ k}\Omega} = 1.76\text{ mA}$

$\beta_{DC} = \dfrac{I_C}{I_B} = \dfrac{1.76\text{ mA}}{63.2\ \mu\text{A}} = \mathbf{27.8}$

(b) $I_B = \dfrac{4.5\text{ V} - 0.7\text{ V}}{27\text{ k}\Omega} = 141\ \mu\text{A}$

$I_C = \dfrac{24\text{ V} - 16.8\text{ V}}{470\ \Omega} = 15.3\text{ mA}$

$\beta_{DC} = \dfrac{I_C}{I_B} = \dfrac{15.3\text{ mA}}{141\ \mu\text{A}} = \mathbf{109}$

Device Application Problems

44. Q_1 OFF, Q_2 ON

$I_{R2} = 0,\ P_{R2} = \mathbf{0\ mW}$
$I_{R1} = 0,\ P_{R2} = \mathbf{0\ mW}$
$I_{R3} = I_{R4} = \dfrac{12\text{ V} - 0.7\text{ V}}{1.2\text{ k}\Omega + 36\text{ k}\Omega} = 304\ \mu\text{A}$
$P_{R3} = (304\ \mu\text{A})^2(1.2\text{ k}\Omega) = \mathbf{110\ \mu W}$
$P_{R4} = (304\ \mu\text{A})^2(36\text{ k}\Omega) = \mathbf{3.3\ mW}$
$I_{R5} = \dfrac{12\text{ V} - 0.176\text{ V}}{620\ \Omega} = 19\text{ mA}$
$P_{R5} = (19\text{ mA})^2(620\ \Omega) = \mathbf{224\ mW}$

Q_1 ON, Q_2 OFF
$I_{R2} = \dfrac{12\text{ V} - 0.7\text{ V}}{75\text{ k}\Omega} = 151\ \mu\text{A}$
$P_{R2} = (151\ \mu\text{A})^2(75\text{ k}\Omega) = \mathbf{1.7\ mW}$
$P_{R1} = \dfrac{(0.7\text{ V})^2}{1.0\text{ M}\Omega} = \mathbf{0.49\ \mu W}$
$I_{R4} \cong \dfrac{12\text{ V} - 0.1\text{ V}}{1.2\text{ k}\Omega} = 9.9\text{ mA}$
$P_{R4} = (9.9\text{ mA})^2(1.2\text{ k}\Omega) = 118\text{ mW}$
$I_{R3} \cong 0,\ P_{R3} = \mathbf{0\ mW}$
$I_{R5} = 0,\ P_{R5} = \mathbf{0\ mW}$

45. $I_{C(max)} = 200$ mA

$$R_{L(min)} = \frac{V_{CC}}{I_{C(max)}} = \frac{12\text{ V}}{200\text{ mA}} = \mathbf{60\ \Omega}$$

46. See Figure 4-2.

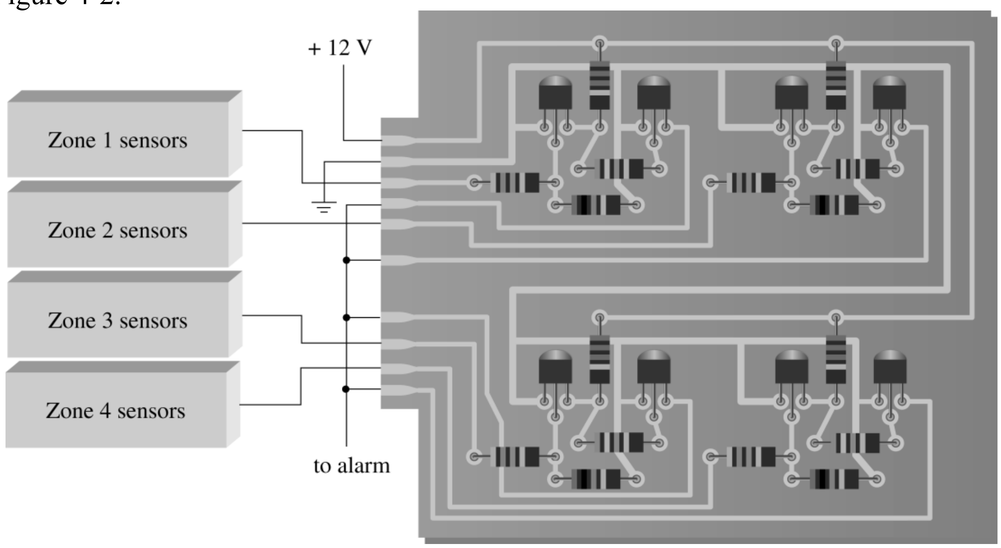

Figure 4-2

Datasheet Problems

47. From the datasheet of textbook Figure 4-20:

(a) For a 2N3904, $V_{CEO(max)} = \mathbf{40\ V}$

(b) For a 2N3904, $I_{C(max)} = \mathbf{200\ mA}$

(c) For a 2N3904 @ 25°C, $P_{D(max)} = \mathbf{625\ mW}$

(d) For a 2N3904 @ $T_C = 50°\text{C}$, $P_{D(max)} = 625\text{ mW} - 5\text{ mW/°C}(25°\text{C})$

$$= 625\text{ mW} - 125\text{ mW} = \mathbf{500\ mW}$$

(e) For a 2N3904 with $I_C = 1$ mA, $h_{FE(min)} = \mathbf{70}$

48. For an MMBT3904 with $T_A = 65°\text{C}$:

$$P_{D(max)} = 350\text{ mW} - (65°\text{C} - 25°\text{C})(2.8\text{ mW/°C})$$
$$= 350\text{ mW} - 40°\text{C}(2.8\text{ mW/°C}) = 350\text{ mW} - 112\text{ mW} = \mathbf{238\ mW}$$

49. For a PZT3904 with $T_C = 45°\text{C}$:

$$P_{D(max)} = 1\text{ W} - (45°\text{C} - 25°\text{C})(8\text{ mW/°C})$$
$$= 1\text{ W} - 20°\text{C}(8\text{ mW/°C}) = 1\text{ W} - 160\text{ mW} = \mathbf{840\ mW}$$

50. For the circuits of textbook Figure 4-67:

(a) $I_B = \dfrac{3\text{ V} - 0.7\text{ V}}{330\ \Omega} = \dfrac{2.3\text{ V}}{330\ \Omega} = 6.97\text{ mA}$

Let $h_{FE} = 30$

$I_C = 30(6.97\text{ mA}) = 209\text{ mA}$

$I_{C(sat)} = \dfrac{V_{CC} - V_{CE(sat)}}{R_C} = \dfrac{30\text{ V} - 0.2\text{ V}}{270\ \Omega} = 110\text{ mA}$

The transistor is saturated since I_C cannot exceed 110 mA.

$P_D = (0.2\text{ V})(110\text{ mA}) = 22\text{ mW}$

At 50°C, $P_{D(max)} = 350\text{ mW} - (50°\text{C} - 25°\text{C})(2.8\text{ mW/°C}) = 280\text{ mW}$

No parameter is exceeded.

(b) $V_{CEO} = 45$ V which **exceeds $V_{CEO(max)}$**.

51. For the circuits of textbook Figure 4-68:

(a) $I_B = \dfrac{5\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = \dfrac{4.3\text{ V}}{10\text{ k}\Omega} = 4.30\ \mu\text{A}$

$h_{FE(max)} = 300$

$I_C = 300(4.30\ \mu\text{A}) = 129\text{ mA}$

$I_{C(sat)} = \dfrac{9\text{ V}}{1.0\text{ k}\Omega} = 9\text{ mA}$

The transistor is saturated.

(b) $I_B = \dfrac{3\text{ V} - 0.7\text{ V}}{100\text{ k}\Omega} = \dfrac{2.3\text{ V}}{100\text{ k}\Omega} = 23\ \mu\text{A}$

$h_{FE(max)} = 300$

$I_C = 300(23\ \mu\text{A}) = 6.90\text{ mA}$

$I_{C(sat)} = \dfrac{12\text{ V}}{560\ \Omega} = 21.4\text{ mA}$

The transistor is not saturated.

52. $I_{B(min)} = \dfrac{I_C}{h_{FE(max)}} = \dfrac{10\text{ mA}}{150} = \mathbf{66.7\ \mu A}$

$I_{B(max)} = \dfrac{I_C}{h_{FE(min)}} = \dfrac{10\text{ mA}}{50} = \mathbf{200\ \mu A}$

53. For the circuits of textbook Figure 4-70:

(a) $I_B = \dfrac{8\text{ V} - 0.7\text{ V}}{68\text{ k}\Omega} = \dfrac{7.3\text{ V}}{68\text{ k}\Omega} = 107\ \mu\text{A}$

$h_{FE} = 150$
$I_C = 150(107\ \mu\text{A}) = 16.1\text{ mA}$
$V_C = 15\text{ V} - (16.1\text{ mA})(680\ \Omega) = 15\text{ V} - 10.95\text{ V} = 4.05\text{ V}$
$V_{CE} = 4.05\text{ V} - 0.7\text{ V} = 3.35\text{ V}$
$P_D = (3.35\text{ V})(16.1\text{ mA}) = 53.9\text{ mW}$
At 40°C, $P_{D(max)} = 360\text{ mW} - (40°\text{C} - 25°\text{C})(2.06\text{ mW/°C}) = 329\text{ mW}$
No parameters are exceeded.

(b) $I_B = \dfrac{5\text{ V} - 0.7\text{ V}}{4.7\text{ k}\Omega} = \dfrac{4.3\text{ V}}{4.7\text{ k}\Omega} = 915\ \mu\text{A}$

$h_{FE} = 300$
$I_C = 300(915\ \mu\text{A}) = 274\text{ mA}$
$I_{C(sat)} \cong \dfrac{35\text{ V} - 0.3\text{ V}}{470\ \Omega} = 73.8\text{ mA}$
The transistor is in hard saturation. Assuming $V_{CE(sat)} = 0.3\text{ V}$,
$P_D = (0.3\text{ V})(73.8\text{ mA}) = 22.1\text{ mW}$
No parameters are exceeded.

Advanced Problems

54. $\beta_{DC} = \dfrac{\alpha_{DC}}{1 - \alpha_{DC}}$

$\beta_{DC} - \beta_{DC}\alpha_{DC} = \alpha_{DC}$
$\beta_{DC} = \alpha_{DC}(1 + \beta_{DC})$
$\alpha_{DC} = \dfrac{\beta_{DC}}{(1 + \beta_{DC})}$

55. $I_C = 150(500\ \mu\text{A}) = \mathbf{75\ mA}$

$V_{CE} = 15\text{ V} - (180\ \Omega)(75\text{ mA}) = \mathbf{1.5\ V}$
Since $V_{CE(sat)} = 0.3\text{ V}$ @ $I_C = 50\text{ mA}$, the transistor comes out of saturation.

56. From the datasheet, $\beta_{DC(min)} = 15$ (for $I_C = 100$ mA)

$$I_{B(max)} = \frac{150\text{ mA}}{15} = 10\text{ mA}$$

$$R_{B(min)} = \frac{3\text{ V} - 0.7\text{ V}}{10\text{ mA}} = \frac{2.3\text{ V}}{10\text{ mA}} = 230\ \Omega$$

Use the standard value of 240 Ω for R_B.

To avoid saturation, the load resistance cannot exceed about

$$\frac{9\text{ V} - 1\text{ V}}{150\text{ mA}} = 53.3\ \Omega$$

See Figure 4-3.

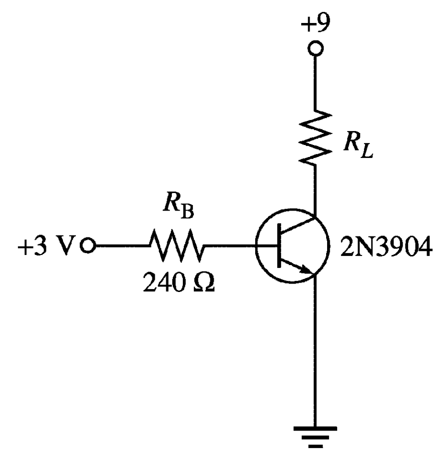

Figure 4-3

57. Since $I_B = 10$ mA for $I_C = 150$ mA,

$$R_{B(min)} = \frac{9\text{ V} - 0.7\text{ V}}{10\text{ mA}} = \frac{8.3\text{ V}}{10\text{ mA}} = 830\ \Omega$$

Use 910 Ω. The load cannot exceed 53.3 Ω.

See Figure 4-4.

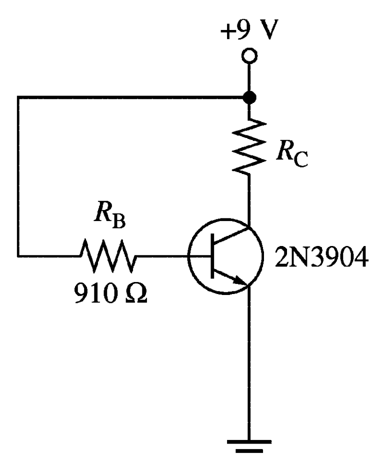

Figure 4-4

58. $R_{C(min)} = A_v r'_e = 50(8\ \Omega) = 400\ \Omega$ (Use 430 Ω)

$$I_C = \frac{12\text{ V} - 5\text{ V}}{430\ \Omega} = 16.3\text{ mA}$$

Assuming $h_{FE} = 100$,

$$I_B = \frac{16.3\text{ mA}}{100} = 163\ \mu\text{A}$$

$$R_{B(max)} = \frac{4\text{ V} - 0.7\text{ V}}{163\ \mu\text{A}} = 20.3\text{ k}\Omega\ \text{(Use 18 k}\Omega\text{)}$$

See Figure 4-5.

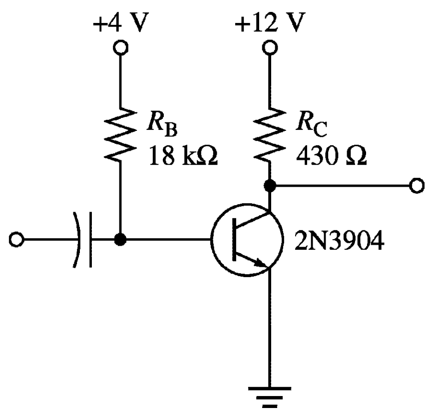

Figure 4-5

Multisim Troubleshooting Problems

59. R_B shorted

60. R_C open

61. Collector-emitter shorted

62. Collector-emitter open

63. R_E leaky

64. Collector-emitter shorted

65. R_B open

66. R_C open

Chapter 5
Transistor Bias Circuits

Section 5-1 The DC Operating Point

1. A transistor must be biased correctly to prevent it from saturating or going into cutoff when an input signal is appliedl.

2. The collector characteristic curve show how the collector current I_C varies with V_{CE} for various values of I_B.

3. The transistor is biased too close to **saturation**.

4. $I_C = \beta_{DC} I_B = 75(150\ \mu\text{A}) = 11.3\ \text{mA}$

$V_{CE} = V_{CC} - I_C R_C = 18\ \text{V} - (11.3\ \text{mA})(1.0\ \text{k}\Omega) = 18\ \text{V} - 11.3\ \text{V} = 6.75\ \text{V}$

Q-point: $V_{CEQ} = \mathbf{6.75\ V}$, $I_{CQ} = \mathbf{11.3\ mA}$

5. $$I_{C(sat)} \cong \frac{V_{CC}}{R_C} = \frac{18\ \text{V}}{1.0\ \text{k}\Omega} = \mathbf{18\ mA}$$

6. $V_{CE(cutoff)} = \mathbf{18\ V}$

7. Horizontal intercept (cutoff):

$V_{CE} = V_{CC} = \mathbf{20\ V}$

Vertical intercept (saturation):

$$I_{C(sat)} = \frac{V_{CC}}{R_C} = \frac{20\ \text{V}}{10\ \text{k}\Omega} = \mathbf{2\ mA}$$

8. $$I_B = \frac{V_{BB} - 0.7\,\text{V}}{R_B}$$

$V_{BB} = I_B R_B + 0.7\ \text{V} = (20\ \mu\text{A})(1.0\ \text{M}\Omega) + 0.7\ \text{V} = \mathbf{20.7\ V}$

$I_C = \beta_{DC} I_B = 50(20\ \mu\text{A}) = \mathbf{1\ mA}$

$V_{CE} = V_{CC} - I_C R_C = 20\ \text{V} - (1\ \text{mA})(10\ \text{k}\Omega) = \mathbf{10\ V}$

9. See Figure 5-1.

$V_{CE} = V_{CC} - I_C R_C$

$$R_C = \frac{V_{CC} - V_{CE}}{I_C} = \frac{10\text{ V} - 4\text{ V}}{5\text{ mA}} = \mathbf{1.2\text{ k}\Omega}$$

$$I_B = \frac{I_C}{\beta_{DC}} = \frac{5\text{ mA}}{100} = 0.05\text{ mA}$$

$$R_B = \frac{10\text{ V} - 0.7\text{ V}}{0.05\text{ mA}} = \mathbf{186\text{ k}\Omega}$$

$$P_{D(min)} = V_{CE} I_C = (4\text{ V})(5\text{ mA}) = \mathbf{20\text{ mW}}$$

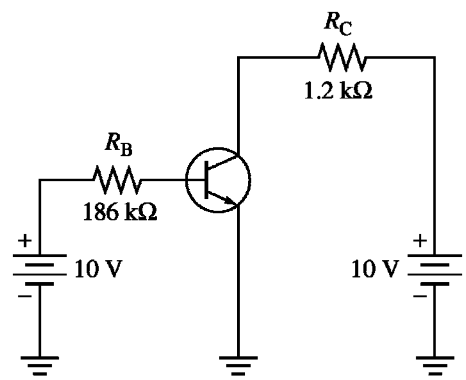

Figure 5-1

10. $$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{1.5\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = 80\ \mu\text{A}$$

$$I_{C(sat)} = \frac{V_{CC}}{R_C} = \frac{8\text{ V}}{390\ \Omega} = 20.5\text{ mA}$$

$$I_C = \beta_{DC} I_B = 75(80\ \mu\text{A}) = 6\text{ mA}$$

The transistor is biased in the linear region because

$0 < I_C < I_{C(sat)}$.

11. (a) $I_{C(sat)} = \mathbf{50\text{ mA}}$

(b) $V_{CE(cutoff)} = \mathbf{10\text{ V}}$

(c) $I_B = \mathbf{250\ \mu A}$

$I_C = \mathbf{25\text{ mA}}$

$V_{CE} = \mathbf{5\text{ V}}$

12. (a) $I_C \cong \mathbf{42\ mA}$

(b) Interpolating between $I_B = 400\,\mu\text{A}$ and $I_B = 500\,\mu\text{A}$

$I_B \cong \mathbf{450\ \mu A}$

(c) $V_{CE} \cong \mathbf{1.5\ V}$

See Figure 5-2.

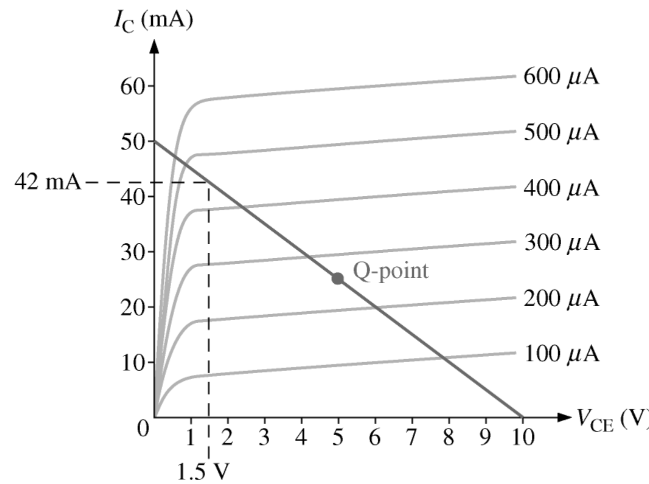

Figure 5-2

Section 5-2 Voltage-Divider Bias

13. $$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{4.7\ \text{k}\Omega}{26.7\ \text{k}\Omega}\right)15\ \text{V} = 2.64\ \text{V}$$

$$R_{TH} = \frac{R_1R_2}{R_1 + R_2} = \frac{(22\ \text{k}\Omega)(4.7\ \text{k}\Omega)}{26.7\ \text{k}\Omega} = 3.87\ \text{k}\Omega$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{2.64\ \text{V} - 0.7\ \text{V}}{680\ \Omega + 3.87\ \text{k}\Omega/150} = 2.75\ \text{mA}$$

$$V_B = I_ER_E + V_{BE} = (2.75\ \text{mA})(680\ \Omega) + 0.7\ \text{V} = 2.57\ \text{V}$$

$$\beta_{DC(min)} = \frac{I_ER_{IN(BASE)}}{V_B} = \frac{(I_E)(10\ R_2)}{V_B} = \frac{(2.75\ \text{mA})(47\ \text{k}\Omega)}{2.57\ \text{V}} = \mathbf{50.3}$$

14. $$I_{C(sat)} = \frac{V_{CC}}{R_C + R_E} = \frac{15\ \text{V}}{2.18\ \text{k}\Omega} = 6.88\ \text{mA}$$

$$V_{E(sat)} = I_{C(sat)}R_E = (6.88\ \text{mA})(680\ \Omega) = 4.68\ \text{V}$$

$$V_B = V_{E(sat)} + 0.7\ \text{V} = 4.68\ \text{V} + 0.7\ \text{V} = 5.38\ \text{V}$$

$$\left(\frac{R_2 \parallel R_{\text{IN(BASE)}}}{R_1 + R_2 \parallel R_{\text{IN(BASE)}}}\right)V_{\text{CC}} = V_{\text{B}}$$

$$R_{\text{IN(BASE)}} = \frac{\beta_{\text{DC}}V_{\text{B}}}{I_{\text{E}}} = \frac{(150)(5.38\text{ V})}{6.88\,\text{mA}} = 117\text{ k}\Omega$$

$$(R_2 \parallel R_{\text{IN(BASE)}})V_{\text{CC}} = V_{\text{B}}(R_1 + R_2 \parallel R_{\text{IN(BASE)}})$$

$$(R_2 \parallel R_{\text{IN(BASE)}})V_{\text{CC}} - (R_2 \parallel R_{\text{IN(BASE)}})V_{\text{B}} = R_1V_{\text{B}}$$

$$(R_2 \parallel R_{\text{IN(BASE)}})(V_{\text{CC}} - V_{\text{B}}) = R_1V_{\text{B}}$$

$$(R_2 \parallel R_{\text{IN(BASE)}}) = \frac{R_1V_{\text{B}}}{V_{\text{CC}} - V_{\text{B}}} = 12.3\text{ k}\Omega$$

$$\frac{1}{R_2} + \frac{1}{R_{\text{IN(BASE)}}} = \frac{1}{12.3\text{ k}\Omega}$$

$$\frac{1}{R_2} = \frac{1}{12.3\text{ k}\Omega} - \frac{1}{117\text{ k}\Omega} = 72.3\,\mu\text{S}$$

$$R_2 = \frac{1}{72.3\,\mu\text{S}} = \mathbf{13.7\text{ k}\Omega}$$

15. $$V_{\text{B}} = \left(\frac{R_2}{R_1 + R_2}\right)V_{\text{CC}} = \left(\frac{2\text{ k}\Omega}{24\text{ k}\Omega}\right)15\text{ V} = 1.25\text{ V}$$

$$V_{\text{E}} = 1.25\text{ V} - 0.7\text{ V} = 0.55\text{ V}$$

$$I_{\text{E}} = \frac{V_{\text{E}}}{R_{\text{E}}} = \frac{0.55\text{ V}}{680\ \Omega} = 809\ \mu\text{A}$$

$$I_{\text{C}} \cong \mathbf{809\ \mu A}$$

$$V_{\text{CE}} = V_{\text{CC}} - I_{\text{C}}R_{\text{C}} - V_{\text{E}} = 15\,\text{V} - (809\ \mu\text{A})(1.5\text{ k}\Omega + 680\ \Omega) = \mathbf{13.2\text{ V}}$$

16. $$V_{\text{TH}} = \left(\frac{R_2}{R_1 + R_2}\right)V_{\text{CC}} = \left(\frac{15\text{ k}\Omega}{62\text{ k}\Omega}\right)9\text{ V} = 2.18\text{ V}$$

$$R_{\text{TH}} = \frac{R_1R_2}{R_1 + R_2} = \frac{(47\text{ k}\Omega)(15\text{ k}\Omega)}{62\text{ k}\Omega} = 11.4\text{ k}\Omega$$

$$I_{\text{E}} = \frac{V_{\text{TH}} - V_{\text{BE}}}{R_{\text{E}} + R_{\text{TH}}/\beta_{\text{DC}}} = \frac{2.18\text{ V} - 0.7\text{ V}}{1\text{ k}\Omega + 11.4\text{ k}\Omega/110} = 1.34\text{ mA}$$

$$I_{\text{C}} \cong I_{\text{E}} = 1.34\,\text{mA}$$

$$V_{\text{C}} = V_{\text{CC}} - I_{\text{C}}R_{\text{C}} = 9\,\text{V} - (1.34\text{ mA})(2.2\text{ k}\Omega) = \mathbf{6.05\text{ V}}$$

$V_E = I_E R_E = (1.34\text{ mA})(1.0\text{ k}\Omega) = \mathbf{1.34\ V}$

$V_B = V_E + V_{BE} = 1.34\text{ V} + 0.7\text{ V} = \mathbf{2.04\ V}$

17. See Figure 5-3.

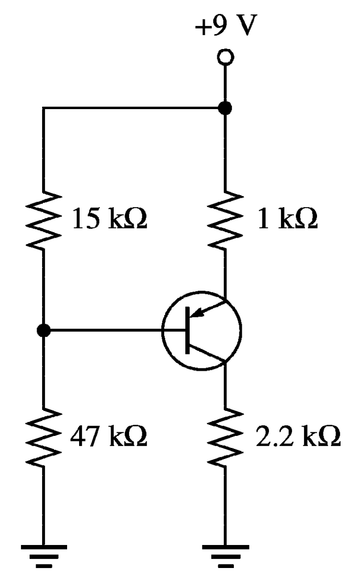

Figure 5-3

18. (a) $V_{TH} = \left(\dfrac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\dfrac{5.6\text{ k}\Omega}{38.6\text{ k}\Omega}\right)(-12\text{ V}) = -1.74\text{ V}$

$R_{TH} = \dfrac{R_1 R_2}{R_1 + R_2} = \dfrac{(5.6\text{ k}\Omega)(33\text{ k}\Omega)}{38.6\text{ k}\Omega} = 4.79\text{ k}\Omega$

$I_E = \dfrac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \dfrac{-1.74\text{ V} - 0.7\text{ V}}{560\ \Omega + 4.79\text{ k}\Omega/150} = -4.12\text{ mA}$

$V_B = I_E R_E + V_{BE} = (-4.12\text{ mA})(560\text{ k}\Omega) + 0.7\text{ V} = -2.31\text{ V} + 0.7\text{ V} = \mathbf{-1.61\ V}$

(b) $I_E = \dfrac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \dfrac{-1.74\text{ V} - 0.7\text{ V}}{560\ \Omega + 4.79\text{ k}\Omega/150} = -3.72\text{ mA}$

$V_B = I_E R_E + V_{BE} = (-3.72\text{ mA})(560\text{ k}\Omega) + 0.7\text{ V} = -2.08\text{ V} + 0.7\text{ V} = \mathbf{-1.38\ V}$

19. (a) $V_{EQ} = V_B + 0.7\text{ V} = -1.61\text{ V} + 0.7\text{ V} = -0.91\text{ V}$

$I_{CQ} \cong I_E = \dfrac{V_{EQ}}{R_E} = \dfrac{0.91\text{ V}}{560\ \Omega} = \mathbf{-1.63\ mA}$

$V_{CQ} = V_{CC} - I_C R_C = -12\text{ V} - (-1.63\text{ mA})(1.8\text{ k}\Omega) = -9.07\text{ V}$

$V_{CEQ} = V_{CQ} - V_{EQ} = -9.07\text{ V} - (-0.91\text{ V}) = \mathbf{-8.16\ V}$

(b) $P_{D(min)} = I_{CQ} V_{CEQ} = (-1.63\text{ mA})(-8.16\text{ V}) = \mathbf{13.3\ mW}$

20. $V_B = -1.61\text{ V}$

$$I_1 = \frac{V_{CC} - V_B}{R_1} = \left|\frac{-12\text{ V} - (-1.61\text{ V})}{33\text{ k}\Omega}\right| = \mathbf{315\ \mu A}$$

$$I_2 = \frac{V_B}{R_2} = \left|\frac{-1.61\text{ V}}{5.6\text{ k}\Omega}\right| = \mathbf{2.88\ \mu A}$$

$$I_B = I_1 - I_2 = 315\ \mu\text{A} - 288\ \mu\text{A} = \mathbf{27\ \mu A}$$

Section 5-3 Other Bias Methods

21. Using Equation 5-9:

$$I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{-(-5\text{ V}) - 0.7\text{ V}}{2.2\text{ k}\Omega + 10\text{ k}\Omega/100} = \frac{4.3\text{ V}}{2.2\text{ k}\Omega + 0.1\text{ k}\Omega} = 1.86\text{ mA}$$

$$I_C \cong I_E = 1.86\text{ mA}$$

$$I_B = \frac{I_C}{\beta} \cong \frac{1.86\text{ mA}}{100} = 18.6\mu\text{A}$$

$$V_B = -I_B R_B = (18.6\ \mu\text{A})(10\text{ k}\Omega) = \mathbf{-0.186\ V}$$

$$V_E = V_B - 0.7\text{ V} = -0.186 - 0.7\text{ V} = \mathbf{-0.886\ V}$$

$$V_C = V_{CC} - I_C R_C = 5\text{ V} - (0.186\text{ mA})(1.0\text{ k}\Omega) = \mathbf{3.14\ V}$$

22. Assume $V_{CE} \cong 0\text{ V}$ at saturation.

$$V_E = -0.886\text{ V}$$

so, $V_{C(sat)} = -0.886$

$$I_{C(sat)} = \frac{V_{CC} - V_{C(sat)}}{R_C} = \frac{5\text{ V} - (-0.886\text{ V})}{1.0\text{ k}\Omega} = 5.89\text{ mA}$$

$$R_{E(min)} = \frac{V_{RE}}{I_{C(sat)}} = \frac{4.11\text{ V}}{5.89\text{ mA}} = \mathbf{698\ \Omega}$$

23. At 100°C:

$$V_{BE} = 0.7\text{ V} - (2.5\text{ mV/°C})(75\text{°C}) = 0.513\text{ V}$$

$$I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{-(-5\text{V}) - 0.513\text{V}}{2.2\text{ k}\Omega + 10\text{k}\Omega/100} = \frac{4.49\text{ V}}{2.3\text{k}\Omega} = 1.95\text{ mA}$$

At 25°C:

$I_E = 1.86\text{ mA}$ (from problem 19)

$$\Delta I_E = 1.95\text{ mA} - 1.86\text{ mA} = \mathbf{0.09\ mA}$$

24. A change in β_{DC} does not affect the circuit when $R_E >> R_B/\beta_{DC}$.

Since

$$I_E = \frac{V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}}$$

In the equation, if R_B/β_{DC} is much smaller than R_E, the effect of β_{DC} is negligible.

25. Assume $\beta_{DC} = 100$.

$$I_C \cong I_E = \frac{V_{EE} - V_E}{R_E + R_B/\beta} = \frac{10\text{ V} - 0.7\text{ V}}{470\ \Omega + 10\text{ k}\Omega/100} = \mathbf{16.3\text{ mA}}$$

$$V_{CE} = V_{EE} - V_{CC} - I_C(R_C + R_E) = 20\text{ V} - 13.1\text{ V} = \mathbf{-6.95\text{ V}}$$

26. $V_B = \mathbf{0.7\text{ V}}$

$$I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}} = \frac{3\text{ V} - 0.7\text{ V}}{1.8\text{k}\Omega + 33\text{ k}\Omega/90} = \mathbf{1.06\text{ mA}}$$

$$V_C = V_{CC} - I_C R_C = 3\text{ V} - (1.06\text{ mA})(1.8\text{ k}\Omega) = \mathbf{1.09\text{ V}}$$

27. $I_C = 1.06$ mA from Problem 26.

$$I_C = 1.06\text{ mA} - (0.25)(1.06\text{ mA}) = 0.795\text{ mA}$$

$$I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}}$$

$$R_C = \frac{V_{CC} - V_{BE} - I_C R_B/\beta_{DC}}{I_C} = \frac{3\text{ V} - 0.7\text{ V} - (0.795\text{ mA})(33\text{ k}\Omega)/90}{0.795\text{ mA}} = \mathbf{2.53\text{ k}\Omega}$$

28. $I_C = 0.795$ mA from Problem 27.

$$V_{CE} = V_{CC} - I_C R_C = 3\text{ V} - (0.795\text{ mA})(2.53\text{ k}\Omega) = 0.989\text{ V}$$

$$P_{D(min)} = V_{CE} I_C = (0.989\text{ V})(0.795\text{ mA}) = \mathbf{786\ \mu W}$$

29. See Figure 5-4.

$$I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}} = \frac{12\text{ V} - 0.7\text{ V}}{1.2\text{ k}\Omega + 47\text{ k}\Omega/200} = \mathbf{7.87\text{ mA}}$$

$$V_C = V_{CC} - I_C R_C = 12\text{ V} - (7.87\text{ mA})(1.2\text{ k}\Omega) = \mathbf{2.56\text{ V}}$$

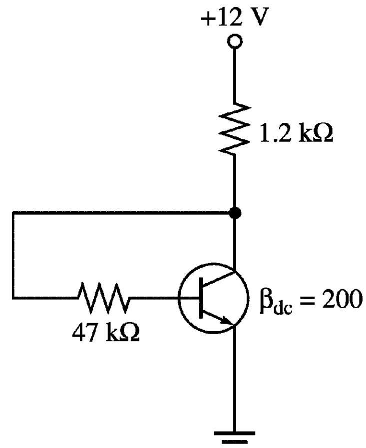

Figure 5-4

30. $V_{BB} = V_{CC};\ V_E = 0\text{ V}$

$$I_B = \frac{V_{CC} - 0.7\text{ V}}{R_B} = \frac{12\text{ V} - 0.7\text{ V}}{22\text{ k}\Omega} = \frac{11.3\text{ V}}{22\text{ k}\Omega} = \mathbf{514\ \mu A}$$

$$I_C = \beta_{DC} I_B = 90(514\ \mu\text{A}) = \mathbf{46.3\text{ mA}}$$

$$V_{CE} = V_{CC} - I_C R_C = 12\text{ V} - (46.3\text{ mA})(100\ \Omega) = \mathbf{7.37\text{ V}}$$

31. $I_{CQ} = 180(514\ \mu\text{A}) = \mathbf{92.5\text{ mA}}$

$$V_{CEQ} = 12\text{ V} - (92.5\text{ mA})(100\ \Omega) = \mathbf{2.75\text{ V}}$$

32. I_C changes in the circuit with a common V_{CC} and V_{BB} supply because a change in V_{CC} causes I_B to change which, in turn, changes I_C.

33. $I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{9\text{ V} - 0.7\text{ V}}{15\text{ k}\Omega} = 553\mu\text{A}$

$$I_{C(sat)} = \frac{V_{CC}}{R_C} = \frac{9\text{ V}}{100\ \Omega} = 90\text{ mA}$$

For $\beta_{DC} = 50$:

$$I_C = \beta_{DC} I_B = 50(553\ \mu\text{A}) = \mathbf{27.7\text{ mA}}$$

$$V_{CE} = V_{CC} - I_C R_C = 9\text{ V} - (27.7\text{ mA})(100\ \Omega) = \mathbf{6.23\text{ V}}$$

For $\beta_{DC} = 125$:

$I_C = \beta_{DC} I_B = 125(553\ \mu\text{A}) = \mathbf{69.2\ mA}$

$V_{CE} = V_{CC} - I_C R_C = 9\ \text{V} - (69.2\ \text{mA})(100\ \Omega) = \mathbf{2.08\ V}$

Since $I_C < I_{C(sat)}$ for the range of β_{DC}, the circuit remains **biased in the linear region**.

34. $I_{C(sat)} = \dfrac{V_{CC}}{R_C} = \dfrac{9\ \text{V}}{100\ \Omega} = 90\ \text{mA}$

At 0°C:

$\beta_{DC} = 110 - 110(0.5) = 55$

$I_B = \dfrac{V_{CC} - V_{BE}}{R_B} = \dfrac{9\ \text{V} - 0.7\ \text{V}}{15\ \text{k}\Omega} = 553\mu\text{A}$

$I_C = \beta_{DC} I_B = 55(553\ \mu\text{A}) = 30.4\ \text{mA}$

$V_{CE} = V_{CC} - I_C R_C = 9\ \text{V} - (30.4\ \text{mA})(100\ \Omega) = 5.96\ \text{V}$

At 70°C:

$\beta_{DC} = 110 + 110(0.75) = 193$

$I_B = 553\ \mu\text{A}$

$I_C = \beta_{DC} I_B = 193(553\ \mu\text{A}) = 107\ \text{mA}$

$I_C > I_{C(sat)}$, therefore the transistor is in saturation at 70°C.

$\Delta I_C = I_{C(sat)} - I_{C(0°)} = 90\ \text{mA} - 30.4\ \text{mA} = \mathbf{59.6\ mA}$

$\Delta V_{CE} \cong V_{CE(0°)} - V_{CE(sat)} = 5.96\ \text{V} - 0\,\text{V} = \mathbf{5.96\ V}$

Section 5-4 Troubleshooting

35. The transistor is off; therefore, $V_1 = \mathbf{0\ V}$, $V_2 = \mathbf{0\ V}$, $V_3 = \mathbf{8\ V}$.

36. $V_1 = \mathbf{0.7\ V}$, $\quad V_2 = \mathbf{0\ V}$

$I_B = \dfrac{8\ \text{V} - 0.7\ \text{V}}{33\ \text{k}\Omega} - \dfrac{0.7\ \text{V}}{10\ \text{k}\Omega} = 221\ \mu\text{A} - 70\ \mu\text{A} = 151\ \mu\text{A}$

$I_C = 200(151\ \mu\text{A}) = 30.2\ \text{mA}$

$I_{C(sat)} = \dfrac{8\ \text{V}}{2.2\ \text{k}\Omega} = 3.64\ \text{mA}$, so $V_C \cong V_E = \mathbf{0\ V}$

If the problem is corrected,

$$V_1 = \left(\frac{10\text{ k}\Omega}{10\text{ k}\Omega + 33\text{ k}\Omega}\right) 8\text{ V} = \mathbf{1.86\text{ V}}$$

$$V_2 = V_E = 1.86\text{ V} - 0.7\text{ V} = \mathbf{1.16\text{ V}}$$

$$I_E = \frac{1.16\text{ V}}{1.0\text{ k}\Omega} = 1.16\text{ mA}$$

$$V_3 = V_C = 8\text{ V} - (1.16\text{ mA})(2.2\text{ k}\Omega) = \mathbf{5.45\text{ V}}$$

37. (a) Open collector

(b) No problems

(c) Transistor shorted from collector-to-emitter

(d) Open emitter

38. For $\beta_{DC} = 35$:

$$V_B = \left(\frac{4.5\text{ k}\Omega}{14.5\text{ k}\Omega}\right)(-10\text{ V}) = -3.1\text{ V}$$

For $\beta_{DC} = 100$:

$$V_B = \left(\frac{5.17\text{ k}\Omega}{15.17\text{ k}\Omega}\right)(-10\text{ V}) = -3.4\text{ V}$$

The measured base voltage at point 4 is within the correct range.

$$V_E = -3.1\text{ V} + 0.7\text{ V} = -2.4\text{ V}$$

$$I_C \cong I_E = \frac{-2.4\text{ V}}{680\ \Omega} = -3.53\text{ mA}$$

$$V_C = -10\text{ V} - (-3.53\text{ mA})(1.0\text{ k}\Omega) = -6.47\text{ V}$$

Allowing for some variation in V_{BE} and for resistor tolerances, the measured collector and emitter voltages are correct.

39. (a) The 680 Ω resistor is open:

Meter 1: **10 V**

Meter 2: **floating**

Meter 3: $V_B = \left(\frac{5.6\text{ k}\Omega}{15.6\text{ k}\Omega}\right)(-10\text{ V}) = \mathbf{-3.59\text{ V}}$

Meter 4: **10 V**

(b) The 5.6 kΩ resistor is open.

$$I_B = \frac{9.3\text{ V}}{10\text{ k}\Omega + 35(680\,\Omega)} = 275\mu\text{A}$$

$I_C = 35(275\mu\text{A}) = 9.6\text{ mA}$

$I_{C(sat)} = \dfrac{10\text{ V}}{1680\,\Omega} = 5.95\text{ mA}$

The transistor is saturated.

Meter 1: **10 V**

Meter 2: (5.95 mA)(680 Ω) = **4.05 V**

Meter 3: 4.05 V + 0.7 V = **4.75 V**

Meter 4: 10 V – (5.95 mA)(1.0 kΩ) = **4.05 V**

(c) The 10 kΩ resistor is open. The transistor is off.

Meter 1: **10 V**

Meter 2: **0 V**

Meter 3: **0 V**

Meter 4: **10 V**

(d) The 1.0 kΩ resistor is open. Collector current is zero.

Meter 1: **10 V**

Meter 2: 1.27 V – 0.7 V = **0.57 V**

Meter 3: $\left(\dfrac{5.6\text{ k}\Omega \parallel 680\,\Omega}{10\text{ k}\Omega + 5.6\text{ k}\Omega \parallel 680\,\Omega}\right)(10\text{ V}) + 0.7\text{ V} = 0.57\text{ V} + 0.7\text{ V} = \mathbf{1.27\text{ V}}$

Meter 4: **floating**

(e) A short from emitter to ground.

Meter 1: **10 V**

Meter 2: **0 V**

Meter 3: **0.7 V**

$I_B \cong \dfrac{(10\text{ V} - 0.7\text{ V})}{10\text{ k}\Omega} = \dfrac{9.3\text{ V}}{10\text{ k}\Omega} = 0.93\text{ mA}$

$I_{C(min)} = 35(0.93\text{ mA}) = 32.6\text{ mA}$

$I_{C(sat)} = \dfrac{10\text{ V}}{1.0\text{ k}\Omega} = 10\text{ mA}$

The transistor is saturated.

Meter 4: $\cong$ **0 V**

(f) An open base-emitter junction. The transistor is off.

Meter 1: **10 V**

Meter 2: **0 V**

Meter 3: $\left(\dfrac{5.6\text{ k}\Omega}{15.6\text{ k}\Omega}\right)(10\text{ V}) = \mathbf{3.59\text{ V}}$

Meter 4: **10 V**

Devices Application Problems

40. With R_1 open:

$V_B = \mathbf{0\ V},\ V_E = \mathbf{0\ V},\ V_C = V_{CC} = \mathbf{9.1\ V}$

41. Faults that will cause the transistor of textbook Figure 5-29(a) to go into cutoff:

R_1 **open**, R_2 **shorted**, base lead or BE junction **open**.

42. At 45°C: $R_{Therm} = 2.7\ k\Omega$

$$V_B\left(\frac{R_{Therm}}{R_1 + R_{Therm}}\right)9\ V = \left(\frac{2.7\ k\Omega}{7.4\ k\Omega}\right)9\ V = 3.28\ V$$

$$V_E = V_B - 0.7\ V = 2.58\ V$$

$$I_E = I_C = \frac{V_E}{R_3} = \frac{2.58\ V}{470\ \Omega} = 5.49\ mA$$

$$V_C = V_{OUT} = 9\ V - (5.49\ mA)(1\ k\Omega) = \mathbf{3.51\ V}$$

At 48°C: $R_{Therm} = 1.78\ k\Omega$

$$V_B = \left(\frac{1.78\ k\Omega}{6.48\ k\Omega}\right)9\ V = 2.47\ V$$

$$V_E = 2.47\ V - 0.7\ V = 1.77\ V$$

$$I_E = I_C = \frac{1.77\ V}{470\ \Omega} = 3.77\ mA$$

$$V_C = V_{OUT} = 9\ V - (3.77\ mA)(1\ k\Omega) = \mathbf{5.23\ V}$$

At 53°C: $R_{Therm} = 1.28\ k\Omega$

$$V_B = \left(\frac{1.28\ k\Omega}{5.98\ k\Omega}\right)9\ V = 1.93\ V$$

$$V_E = 1.93\ V - 0.7\ V = 1.23\ V$$

$$I_E = I_C = \frac{1.23\ V}{470\ \Omega} = 2.62\ mA$$

$$V_C = V_{OUT} = 9\ V - (2.62\ mA)(1\ k\Omega) = \mathbf{6.38\ V}$$

43. The following measurements would indicate an open CB junction:

$V_C = V_{CC} = \mathbf{+9.1\ V}$

V_B **normal**

$V_E \cong \mathbf{0\ V}$

Chapter 5

Datasheet Problems

44. For $T = 45°\text{C}$ and $R_2 = 2.7\ \text{k}\Omega$

$$R_{\text{IN(base)}} = 2.7\,\text{k}\Omega \parallel (30)(470\ \Omega) = 2.7\ \text{k}\Omega \parallel 14.1\ \text{k}\Omega = 2.27\ \text{k}\Omega\ \text{min}$$

$$R_{\text{IN(base)}} = 2.7\ \text{k}\Omega \parallel (300)(470\ \Omega) = 2.7\ \text{k}\Omega \parallel 141\ \text{k}\Omega = 2.65\ \text{k}\Omega\ \text{max}$$

$$V_{\text{B(min)}} = \left(\frac{2.27\ \text{k}\Omega}{2.27\ \text{k}\Omega + 5.6\ \text{k}\Omega}\right)9.1\ \text{V} = \left(\frac{2.27\ \text{k}\Omega}{7.87}\right)9.1\ \text{V} = \mathbf{2.62\ V}$$

$$V_{\text{E(min)}} = 2.62\ \text{V} - 0.7\ \text{V} = \mathbf{1.92\ V}$$

$$\text{So, } I_C \cong I_E = \frac{1.92\ \text{V}}{470\ \Omega} = 4.09\ \text{mA}$$

$$V_{\text{C(max)}} = 9.1\ \text{V} - (4.09\ \text{mA})(1.0\ \text{k}\Omega) = \mathbf{5.01\ V}$$

$$V_{\text{B(max)}} = \left(\frac{2.65\ \text{k}\Omega}{2.65\ \text{k}\Omega + 5.6\ \text{k}\Omega}\right)9.1\ \text{V} = \left(\frac{2.65\ \text{k}\Omega}{8.25\ \text{k}\Omega}\right)9.1\ \text{V} = \mathbf{2.62\ V}$$

$$V_{\text{E(max)}} = 2.92\ \text{V} - 0.7\ \text{V} = \mathbf{2.22\ V}$$

$$\text{So, } I_C \cong I_E = \frac{2.22\ \text{V}}{470\ \Omega} = 4.73\ \text{mA}$$

$$V_{\text{C(min)}} = 9.1\ \text{V} - (4.73\ \text{mA})(1.0\ \text{k}\Omega) = \mathbf{4.37\ V}$$

For $T = 55°\text{C}$ and $R_2 = 1.24\ \text{k}\Omega$:

$$R_{\text{IN(base)}} = 1.24\ \text{k}\Omega \parallel (30)(470\ \Omega) = 1.24\ \text{k}\Omega \parallel 14.1\ \text{k}\Omega = 1.14\ \text{k}\Omega\ \text{min}$$

$$R_{\text{IN(base)}} = 1.24\ \text{k}\Omega \parallel (300)(470\ \Omega) = 1.24\ \text{k}\Omega \parallel 141\ \text{k}\Omega = 1.23\ \text{k}\Omega\ \text{max}$$

$$V_{\text{B(min)}} = \left(\frac{1.14\ \text{k}\Omega}{1.14\ \text{k}\Omega + 5.6\ \text{k}\Omega}\right)9.1\ \text{V} = \left(\frac{1.14\ \text{k}\Omega}{6.74\ \text{k}\Omega}\right)9.1\ \text{V} = \mathbf{1.54\ V}$$

$$V_{\text{E(min)}} = 1.54\ \text{V} - 0.7\ \text{V} = \mathbf{0.839\ V}$$

$$\text{So, } I_C \cong I_E = \frac{0.839\ \text{V}}{470\ \Omega} = 1.78\ \text{mA}$$

$$V_{\text{C(max)}} = 9.1\ \text{V} - (1.78\ \text{mA})(1.0\ \text{k}\Omega) = \mathbf{7.32\ V}$$

$$V_{\text{B(max)}} = \left(\frac{1.23\ \text{k}\Omega}{1.23\ \text{k}\Omega + 5.6\ \text{k}\Omega}\right)9.1\ \text{V} = \left(\frac{1.23\ \text{k}\Omega}{6.83\ \text{k}\Omega}\right)9.1\ \text{V} = \mathbf{1.64\ V}$$

$$V_{\text{E(max)}} = 1.64\ \text{V} - 0.7\ \text{V} = \mathbf{0.938\ V}$$

$$\text{So, } I_C \cong I_E = \frac{0.938\ \text{V}}{470\ \Omega} = 2.0\ \text{mA}$$

$$V_{\text{C(min)}} = 9.1\ \text{V} - (2.0\ \text{mA})(1.0\ \text{k}\Omega) = \mathbf{7.10\ V}$$

45. At $T = 45°\text{C}$ for minimum β_{DC}:

$$P_{\text{D(max)}} = (5.01\text{ V} - 1.92\text{ V})(4.09\text{ mA}) = (3.09\text{ V})(4.09\text{ mA}) = 12.6\text{ mW}$$

At $T = 55°\text{C}$ for minimum β_{DC}:

$$P_{\text{D(max)}} = (7.32\text{ V} - 0.839\text{ V})(1.78\text{ mA}) = (6.48\text{ V})(1.78\text{ mA}) = 11.5\text{ mW}$$

For maximum beta values, the results are comparable and nowhere near the maximum.

$$P_{\text{D(max)}} = 625\text{ mW} - (5.0\text{ m/°C})(30°\text{C}) = 475\text{ mW}$$

No ratings are exceeded.

46. For the datasheet of Figure 5-49 in the textbook:

(a) For a 2N2222A, $I_{\text{C(max)}} = \mathbf{1\ A}$ continuous

(b) For a 2N2118A, $V_{\text{EB(max)}} = \mathbf{6.0\ V}$

47. For a 2N2222A @ $T = 100°\text{C}$:

$$P_{\text{D(max)}} = 0.8\text{ W} - (4.57\text{ mW/°C})(100°\text{C} - 25°\text{C}) = 0.8\text{ W} - 343\text{ mW} = \mathbf{457\ mW}$$

48. If I_{C} changes from 1 mA to 500 mA in a 2N2219A, the percentage change in β_{DC} is

$$\Delta\beta_{\text{DC}} = \left(\frac{30 - 50}{50}\right)100\% = \mathbf{-40\%}$$

Advanced Problems

49. See Figure 5-5.

$$R_{\text{C}} = \frac{V_{\text{CC}} - V_{\text{CEQ}}}{I_{\text{CQ}}} = \frac{15\text{ V} - 5\text{ V}}{5\text{ mA}} = 2\text{ k}\Omega$$

Assume $\beta_{\text{DC}} = 100$.

$$I_{\text{BQ}} = \frac{I_{\text{CQ}}}{\beta_{\text{DC}}} = \frac{5\text{ mA}}{100} = 50\ \mu\text{A}$$

$$R_{\text{B}} = \frac{V_{\text{CC}} - V_{\text{BE}}}{I_{\text{BQ}}} = \frac{15\text{ V} - 0.7\text{ V}}{50\ \mu\text{A}} = 286\text{ k}\Omega$$

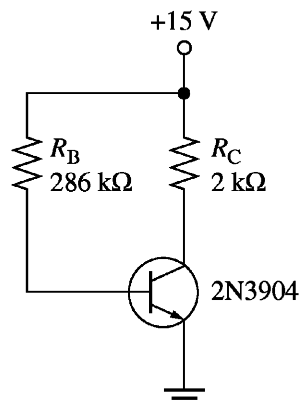

Figure 5-5

50. See Figure 5-6.

Assume $\beta_{DC} = 200$.

$$I_{BQ} = \frac{I_{CQ}}{\beta_{DC}} = \frac{10\text{ mA}}{200} = 50\ \mu\text{A}$$

Let $R_B = 1.0\text{ k}\Omega$

$$R_E = \frac{12\text{ V} - (50\ \mu\text{A})(1.0\text{ k}\Omega) - 0.7\text{ V}}{10\text{ mA}} = \frac{11.3\text{ V}}{10\text{ mA}} = 1.13\text{ k}\Omega$$

$$R_C = \frac{12\text{ V} - (-12\text{ V} + 11.3\text{ V} + 4\text{ V})}{10\text{ mA}} = \frac{8.7\text{ V}}{10\text{ mA}} = 870\ \Omega$$

870 Ω and 1.13 kΩ are not standard values. $R_C = 820\ \Omega$ and $R_E = 1.2\text{ k}\Omega$ give $I_{CQ} \cong 9.38\text{ mA}$, $V_{CEQ} \cong 5.05\text{ V}$.

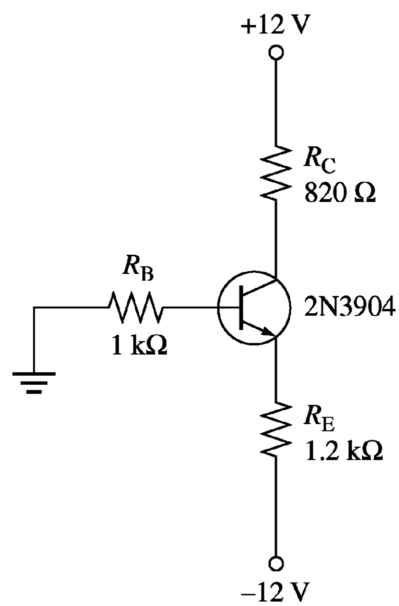

Figure 5-6

51. See Figure 5-7.

$\beta_{DC(min)} \cong 70$. Let $R_E = 1.0\text{ k}\Omega$.

$$V_E = I_E R_E = 1.5\text{ mA}(1.0\text{ k}\Omega) = 1.5\text{ V}$$

$$V_B = 1.5\text{ V} + 0.7\text{ V} = 2.2\text{ V}$$

$$R_C = \frac{V_{CC} - V_{CEQ} - V_E}{I_{CQ}} = \frac{9\text{ V} - 1.5\text{ V} - 3\text{ V}}{1.5\text{ mA}} = 3\text{ k}\Omega$$

$$R_1 + R_2 = \frac{V_{CC}}{I_{CC(max)} - I_{CQ}} = \frac{9\text{ V}}{5\text{ mA} - 1.5\text{ mA}} = 2.57\text{ k}\Omega\text{ min}$$

Assume $\beta_{DC}R_E >> R_2$. The ratio of bias resistors equals the ratio of the voltages as follows.

$$\frac{R_1}{R_2} = \frac{6.8\text{ V}}{2.2\text{ V}} = 3.09$$

$$R_1 = 3.09R_2$$

$$R_1 + R_2 = R_2 + 3.09R_2 = 2.57\text{ k}\Omega$$

$$4.09R_2 = 2.57\text{ k}\Omega$$

$$R_2 = \frac{2.57\text{ k}\Omega}{4.09} = 628\ \Omega$$

So, $R_2 \cong 620\ \Omega$ and $R_1 \cong 1.92\text{ k}\Omega \cong 2\text{ k}\Omega$.

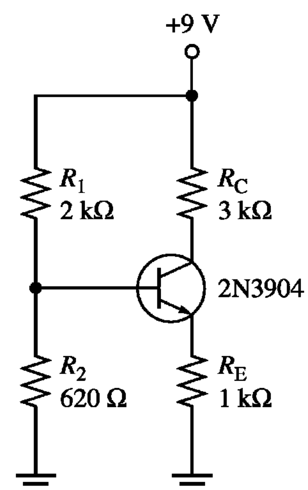

Figure 5-7

From this,

$$R_{\text{IN(base)}} = \frac{\beta_{DC}V_B}{I_E} = \frac{(70)(2.2\text{ V})}{1.5\text{ mA}} = 103\text{ kW} >> R_2$$

so, $V_B = \left(\dfrac{620\ \Omega}{2.62\text{ k}\Omega}\right)9\text{ V} = 2.13\text{ V}$

$$V_E = 2.13\text{ V} - 0.7\text{ V} = 1.43\text{ V}$$

$$I_{CQ} \cong I_E = \frac{1.43\text{ V}}{1.0\text{ k}\Omega} = 1.43\text{ mA}$$

$$V_{CEQ} = 9\text{ V} - (1.43\text{ mA})(1.0\text{ k}\Omega + 3\text{ k}\Omega) = 3.28\text{ V}$$

52. See Figure 5-8.

$\beta_{DC} \cong 75.$

$$I_{BQ} = \frac{10 \text{ mA}}{75} = 133\ \mu\text{A}$$

$$R_C = \frac{V_{CC} - V_{CE}}{I_{CQ}} = \frac{5\text{ V} - 1.5\text{ V}}{10\text{ mA}} = 350\ \Omega \text{ (use 360 }\Omega)$$

$$R_B = \frac{V_{CE} - 0.7\text{ V}}{I_{BQ}} = \frac{1.55\text{ V} - 0.7\text{ V}}{133\ \mu\text{A}} = 6\text{ k}\Omega \text{ (use 6.2 k}\Omega)$$

$$I_{CQ} = \frac{5\text{ V} - 0.7\text{ V}}{360\ \Omega + 6.2\text{ k}\Omega/75} = 9.71\text{ mA}$$

$$V_{CEQ} = V_C = 5\text{ V} - (9.71\text{ mA})(360\ \Omega) = 1.50\text{ V}$$

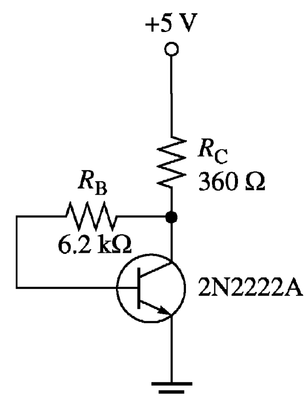

Figure 5-8

53. The 2N3904 in textbook Figure 5-47 **can be replaced** with a 2N2222A and maintain the same voltage range from 45°C to 55°C because the voltage-divider circuit is essentially β independent and the β_{DC} parameters of the two transistors are comparable.

54. For the 2N2222A using the datasheet graph in textbook Figure 5-50 at I_C = 150 mA and V_{CE} = 1.0 V:

At T = –55°C, $h_{FE(min)}$ = (0.45)(50) = **22.5**

At T = 25°C, $h_{FE(min)}$ = (0.63)(50) = **31.5**

At T = 175°C, $h_{FE(min)}$ = (0.53)(50) = **26.6**

55. If the valve interface circuit loading of the temperature conversion circuit changes from 100 kΩ to 10 kΩ, the Q-point will have a reduced V_{CEQ} because the current through R_C will consist of the same I_C and a larger I_L. I_{CQ} is unaffected in the sense that the transistor collector current is the same, although the collector resistance current is larger. The transistor saturates sooner so that lower temperatures do not register as well, if at all.

56. It is not feasible to operate the circuit from a 5.1 V dc supply and maintain the same range of output voltages because the output voltage at 60°C must be 6.478 V.

Multisim Troubleshooting Problems

57. R_C open

58. R_B open

59. R_2 open

60. Collector-emitter shorted

61. R_C shorted

62. Base-emitter open

Chapter 6
BJT Amplifiers

Section 6-1 Amplifier Operation

1. Slightly greater than **1 mA** minimum

2. From the graph of Figure 6-4, the highest value of dc collector current is about **6 mA**.

3. One end of the ac load line intersects the horizontal axis at $V_{\mathrm{ce(curoff)}}$. The other end intersects the vertical axis at $I_{\mathrm{c(sat)}}$.

Section 6-2 Transistor AC Models

4. The *r* parameters are r_e' (ac emitter resistance), r_c' (ac collector resistance), r_b' (ac base resistance), alphaac (ac alpha), betaac (ac beta). The h parameters are hi (input impedance), hr (voltage feedback ratio), hf (forward current gain), ho (outut admittance)

5. $$r_e' = \frac{25\text{ mV}}{I_{\mathrm{E}}} = \frac{25\text{ mV}}{3\text{ mA}} = \mathbf{8.33\ \Omega}$$

6. $$\beta_{ac} = h_{fe} = \mathbf{200}$$

7. $$I_{\mathrm{C}} = \beta_{\mathrm{DC}} I_{\mathrm{B}} = 130(10\ \mu\text{A}) = 1.3\text{ mA}$$

$$I_{\mathrm{E}} = \frac{I_{\mathrm{C}}}{\alpha_{\mathrm{DC}}} = \frac{1.3\text{ mA}}{0.99} = 1.31\text{ mA}$$

$$r_e' = \frac{25\text{ mV}}{I_{\mathrm{E}}} = \frac{25\text{ mV}}{1.31\text{ mA}} = \mathbf{19\ \Omega}$$

8. $$\beta_{\mathrm{DC}} = \frac{I_{\mathrm{C}}}{I_{\mathrm{B}}} = \frac{2\text{ mA}}{15\ \mu\text{A}} = \mathbf{133}$$

$$\beta_{ac} = \frac{\Delta I_{\mathrm{C}}}{\Delta I_{\mathrm{B}}} = \frac{0.35\text{ mA}}{3\ \mu\text{A}} = \mathbf{117}$$

Section 6-3 The Common-Emitter Amplifier

9. See Figure 6-1.

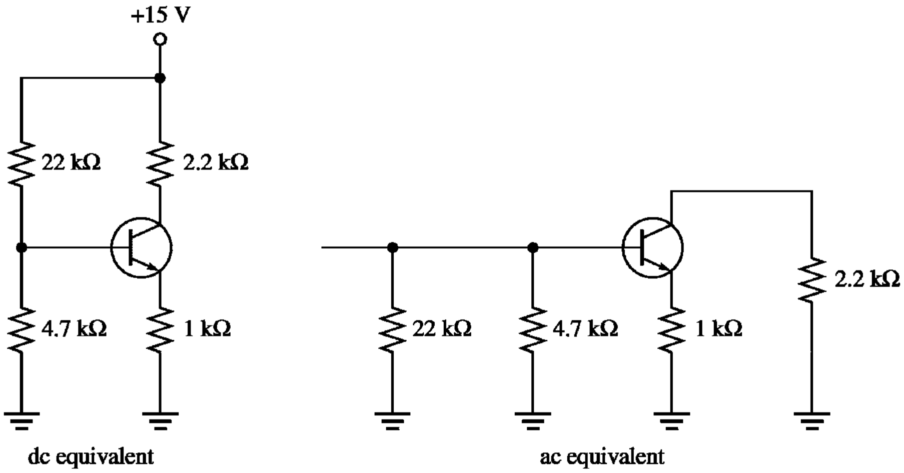

Figure 6-1

10. (a) $V_B = \left(\dfrac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\dfrac{4.7\text{ k}\Omega}{26.7\text{ k}\Omega}\right)15\text{ V} = \mathbf{2.64\ V}$

(b) $V_E = V_B - 0.7\text{ V} = 2.64 - 0.7\text{ V} = \mathbf{1.94\ V}$

(c) $I_E = \dfrac{V_E}{R_E} = \dfrac{1.94\text{ V}}{1.0\text{ k}\Omega} = \mathbf{1.94\ mA}$

(d) $I_C \cong I_E = \mathbf{1.94\ mA}$

(e) $V_C = V_{CC} - I_C R_C = 15\text{ V} - (1.94\text{ mA})(2.2\text{ k}\Omega) = \mathbf{11.6\ V}$

11. $I_{CC} = I_{BIAS} + I_C$

$$I_{BIAS} = \frac{V_B}{R_2} = \frac{2.64\text{ V}}{4.7\text{ k}\Omega} = 562\ \mu\text{A}$$

$I_{CC} = 562\ \mu\text{A} + 1.94\text{ mA} = 2.50\text{ mA}$

$P = I_{CC}V_{CC} = (2.5\text{ mA})(15\text{ V}) = \mathbf{37.5\ mW}$

12. (a) $V_B = \left(\dfrac{4.7\text{ k}\Omega}{4.7\text{ k}\Omega + 22\text{ k}\Omega}\right)15\text{ V} = 2.64\text{ V}$

$V_E = 2.64\text{ V} - 0.7\text{ V} = 1.94\text{ V}$

$$I_E = \frac{1.94\text{ V}}{1.0\text{ k}\Omega} = 1.94\text{ mA}$$

$$r'_e \cong \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{1.94\text{ mA}} = 12.9\ \Omega$$

$$R_{in(base)} = \beta_{ac}\left(r'_e + R_E\right) = 100(1012.9\ \Omega) \cong \mathbf{101\ k\Omega}$$

(b) $R_{in} = R_{in(base)} \parallel R_1 \parallel R_2 = 101\ \text{k}\Omega \parallel 22\ \text{k}\Omega \parallel 4.7\ \text{k}\Omega = \mathbf{3.73\ k\Omega}$

(c) $A_v = \dfrac{R_C}{R_E + r'_e} = \dfrac{2.2\ \text{k}\Omega}{12.02\ \Omega} = \mathbf{2.17}$

13. (a) $R_{in(base)} = \beta_{ac} r'_e = 100(12.9\ \Omega) = \mathbf{1.29\ k\Omega}$

(b) $R_{in} = 1.29\ \text{k}\Omega \parallel 22\ \text{k}\Omega \parallel 4.7\ \text{k}\Omega = \mathbf{968\ \Omega}$

(c) $A_v = \dfrac{R_C}{r'_e} = \dfrac{2.2\ \text{k}\Omega}{12.9\ \Omega} = \mathbf{171}$

14. (a) $R_{in(base)} = \beta_{ac} r'_e = 100(12.9\ \Omega) = \mathbf{1.29\ k\Omega}$

(b) $R_{in} = 1.29\ \text{k}\Omega \parallel 22\ \text{k}\Omega \parallel 4.7\ \text{k}\Omega = \mathbf{968\ \Omega}$

(c) $A_v = \dfrac{R_c}{r'_e} = \dfrac{R_C \parallel R_L}{r'_e} = \dfrac{2.2\ \text{k}\Omega \parallel 10\ \text{k}\Omega}{12.9\ \Omega} = \mathbf{140}$

15. (a) $V_{TH} = \left(\dfrac{R_2}{R_1 + R_2}\right) V_{CC} = \left(\dfrac{12\ \text{k}\Omega}{59\ \text{k}\Omega}\right) 18\ \text{V} = 3.66\ \text{V}$

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = \frac{(47\ \text{k}\Omega)(12\ \text{k}\Omega)}{59\ \text{k}\Omega} = 9.56\ \text{k}\Omega$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{3.66\ \text{V} - 0.7\ \text{V}}{1\ \text{k}\Omega + 9.56\ \text{k}\Omega/75} = \mathbf{2.63\ mA}$$

(b) $V_E = I_E R_E = (2.63\ \text{mA})(1\ \text{k}\Omega) = \mathbf{2.63\ V}$

(c) $V_B = V_E + V_{BE} = 2.63\ \text{V} + 0.7\ \text{V} = \mathbf{3.76\ V}$

(d) $I_C \cong I_E = \mathbf{2.63\ mA}$

(e) $V_C = V_{CC} - I_C R_C = 18\ \text{V} - (2.63\ \text{mA})(3.3\ \text{kW}) = \mathbf{9.32\ V}$

(f) $V_{CE} = V_C - V_E = 9.32\ \text{V} - 2.63\ \text{V} = \mathbf{6.69\ V}$

16. From Problem 15, $I_E = 2.63$ mA

(a) $R_{in(base)} = \beta_{ac} r'_e \cong \beta_{ac}\left(\dfrac{25\ \text{mV}}{I_E}\right) = 70\left(\dfrac{25\ \text{mV}}{2.63\ \text{mA}}\right) = \mathbf{665\ \Omega}$

(b) $R_{in} = R_1 \parallel R_2 \parallel R_{in(base)} = 47\ \text{k}\Omega \parallel 12\ \text{k}\Omega \parallel 665\ \Omega = \mathbf{622\ \Omega}$

(c) $A_v = \dfrac{R_C \parallel R_L}{r'_e} = \dfrac{3.3\ \text{k}\Omega \parallel 10\ \text{k}\Omega}{9.5\ \Omega} = \mathbf{261}$

(d) $A_i = \beta_{ac} = \mathbf{70}$

(e) $A_p = A_v A_i = (261)(70) = \mathbf{18{,}270}$

17. $$V_b = \left(\frac{R_{in}}{R_{in}+R_s}\right)V_{in} = \left(\frac{640\ \Omega}{640\ \Omega + 600\ \Omega}\right)12\ \mu\text{V}$$

Attenuation of the input network is

$$\left(\frac{R_{in}}{R_{in}+R_s}\right) = \left(\frac{640\ \Omega}{640\ \Omega + 600\ \Omega}\right) = 0.516$$

$$A_v' = 0.516A_v = 0.516(253) = \mathbf{131}$$

$\theta = \mathbf{180°}$

18. $$V_{\text{TH}} = \left(\frac{R_2}{R_1+R_2}\right)V_{\text{CC}} = \left(\frac{3.3\ \text{k}\Omega}{15.3\ \text{k}\Omega}\right)8\ \text{V} = 1.73\ \text{V}$$

$$R_{\text{TH}} = \frac{R_1R_2}{R_1+R_2} = \frac{(12\ \text{k}\Omega)(3.3\ \text{k}\Omega)}{15.3\ \text{k}\Omega} = 2.59\ \text{k}\Omega$$

$$I_{\text{E}} = \frac{V_{\text{TH}} - V_{\text{BE}}}{R_{\text{E}} + R_{\text{TH}}/\beta_{\text{DC}}} = \frac{1.73\ \text{V} - 0.7\ \text{V}}{100\ \Omega + 2.59\ \text{k}\Omega/150} = \mathbf{8.78\ mA}$$

$$r_e' = \frac{25\ \text{mV}}{I_{\text{E}}} = \frac{25\ \text{mV}}{8.78\ \text{mA}} = 2.85\ \Omega$$

Maximum gain is at $R_e = 0\ \Omega$

$$A_{v(\max)} = \frac{R_{\text{C}}}{r_e'} = \frac{330\ \Omega}{2.85\ \Omega} = \mathbf{116}$$

Minimum gain is at $R_e = 100\ \Omega$.

$$A_{v(\min)} = \frac{R_{\text{C}}}{R_{\text{E}} + r_e'} = \frac{330\ \Omega}{2.85\ \Omega} = \mathbf{3.21}$$

19. $$V_{\text{TH}} = \left(\frac{R_2}{R_1+R_2}\right)V_{\text{CC}} = \left(\frac{3.3\ \text{k}\Omega}{15.3\ \text{k}\Omega}\right)8\ \text{V} = 1.73\ \text{V}$$

$$R_{\text{TH}} = \frac{R_1R_2}{R_1+R_2} = \frac{(12\ \text{k}\Omega)(3.3\ \text{k}\Omega)}{15.3\ \text{k}\Omega} = 2.59\ \text{k}\Omega$$

$$I_{\text{E}} = \frac{V_{\text{TH}} - V_{\text{BE}}}{R_{\text{E}} + R_{\text{TH}}/\beta_{\text{DC}}} = \frac{1.73\ \text{V} - 0.7\ \text{V}}{100\ \Omega + 2.59\ \text{k}\Omega/150} = \mathbf{8.78\ mA}$$

$$r_e' = \frac{25\ \text{mV}}{I_{\text{E}}} = \frac{25\ \text{mV}}{8.78\ \text{mA}} = 2.85\ \Omega$$

Maximum gain is at $R_e = 0\ \Omega$

$$A_{v(\max)} = \frac{R_{\text{C}} \parallel R_L}{r_e'} = \frac{330\ \Omega \parallel 600\ \Omega}{2.85\ \Omega} = \mathbf{74.7}$$

Minimum gain is at R_e = 100 Ω.

$$A_{v(\min)} = \frac{R_C \parallel R_L}{R_E + r_e'} = \frac{213\ \Omega}{102.85\ \Omega} = \mathbf{2.07}$$

20. $R_{in} = R_1 \parallel R_2 \parallel \beta_{ac} r_e' = 3.3\ \text{k}\Omega \parallel 12\ \text{k}\Omega \parallel 150(3.25\ \Omega) = 410\ \Omega$

Attenuation of the input network is

$$\frac{R_{in}}{R_{in} + R_s} = \frac{410\,\Omega}{410\ \Omega + 300\ \Omega} = 0.578$$

$$A_v = \frac{R_c}{r_e'} = \frac{330\ \Omega \parallel 1.0\ \text{k}\Omega}{3.25\ \Omega} = 76.3$$

$$A_v' = 0.5777 A_v = 0.578(76.3) = \mathbf{44.1}$$

21. See Figure 6-2.

$$r_e' \cong \frac{25\ \text{mV}}{2.55\ \text{mA}} = 9.8\ \Omega$$

$$R_e \geq 10 r_e'$$

Set R_e = 100 Ω

The gain is reduced to

$$A_v = \frac{R_C}{R_e + r_e'} = \frac{3.3\ \text{k}\Omega}{109.8\ \Omega} = 30.1$$

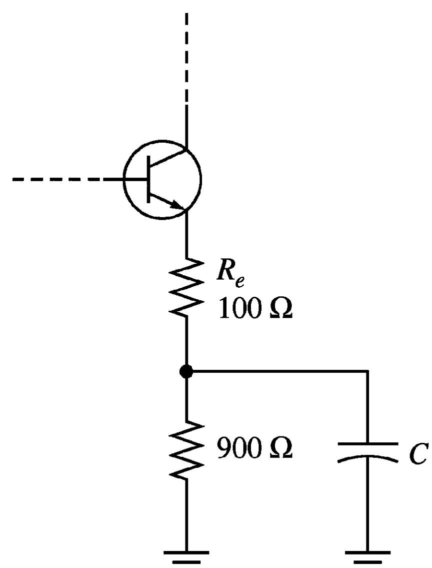

Figure 6-2

Section 6-4 The Common-Collector Amplifier

22. $V_B = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{4.7\text{ k}\Omega}{14.7\text{ k}\Omega}\right)5.5\text{ V} = 1.76\text{ V}$

$I_E = \frac{V_B - 0.7\text{ V}}{R_E} = \frac{1.76\text{ V} - 0.7\text{ V}}{1.0\text{ k}\Omega} = 1.06\text{ mA}$

$r'_e \cong \frac{25\text{ mV}}{1.06\text{ mA}} = 23.6\ \Omega$

$A_v = \frac{R_E}{R_E + r'_e} = \frac{1.0\text{ k}\Omega}{1.0\text{ k}\Omega + 23.6\ \Omega} = \mathbf{0.977}$

23. $R_{in} = R_1 \| R_2 \| \beta_{ac}(r'_e + R_E) \cong R_1 \| R_2 \| \beta_{ac}R_E = 10\text{ k}\Omega \| 4.7\text{ k}\Omega \| 100\text{ k}\Omega = \mathbf{3.1\text{ k}\Omega}$

$V_{OUT} = V_B - 0.7\text{ V} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} - 0.7\text{ V} = \left(\frac{4.7\text{ k}\Omega}{14.7\text{ k}\Omega}\right)5.5\text{ V} - 0.7\text{ V} = \mathbf{1.06\text{ V}}$

24. The voltage gain is **reduced** because $A_v = \frac{R_e}{R_e + r'_e}$.

25. $V_B = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{4.7\text{ k}\Omega}{14.7\text{ k}\Omega}\right)5.5\text{ V} = 1.76\text{ V}$

$I_E = \frac{V_B - V_{BE}}{R_E} = \frac{1.76\text{ V} - 0.7\text{ V}}{1.0\text{ k}\Omega} = 1.06\text{ mA}$

$r'_e \cong \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{1.06\text{ mA}} = 23.6\ \Omega$

$A_v = \frac{R_E \| R_L}{r'_e + R_E \| R_L}$

$A_v(r'_e + R_E \| R_L) = R_E \| R_L$

$R_E \| R_L - A_v(R_E \| R_L) = A_v r'_e$

$(R_E \| R_L)(1 - A_v) = A_v r'_e$

$(R_E \| R_L) = \frac{A_v r'_e}{(1 - A_v)} = \frac{09(23.6\ \Omega)}{1 - 0.9} = 212.4\ \Omega$

$R_L R_E = 212.4R_L + 212.4R_E$

$R_L R_E - 212.4R_L = 212.4R_E$

$R_L = \frac{212.4R_E}{R_E - 212.4} = \frac{(212.4\ \Omega)(1000\ \Omega)}{1000\ \Omega - 212.4\ \Omega} = \mathbf{270\ \Omega}$

26. (a) $V_{C1} = \mathbf{10\ V}$

$$V_{B1} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{22\text{ k}\Omega}{55\text{ k}\Omega}\right)10\text{ V} = \mathbf{4\ V}$$

$V_{E1} = V_{B1} - 0.7\text{ V} = 4\text{ V} - 0.7\text{ V} = \mathbf{3.3\ V}$

$V_{C2} = \mathbf{10\ V}$

$V_{B2} = V_{E1} = \mathbf{3.3\ V}$

$V_{E2} = V_{B2} - 0.7\text{ V} = 3.3\text{ V} - 0.7\text{ V} = \mathbf{2.6\ V}$

(b) $\beta'_{DC} = \beta_{DC1}\beta_{DC2} = (150)(100) = \mathbf{15{,}000}$

(c) $$I_{E1} = \frac{V_{E1} - 0.7\text{ V}}{\beta_{DC2}R_E} = \frac{2.6\text{ V}}{100(1.5\text{ k}\Omega)} = 17.3\ \mu\text{A}$$

$$r'_{e1} \cong \frac{25\text{ mV}}{I_{E1}} = \frac{25\text{ mV}}{17.3\ \mu\text{A}} = \mathbf{1.45\ k\Omega}$$

$$I_{E2} = \frac{V_{E2}}{R_E} = \frac{2.6\text{ V}}{1.5\text{ k}\Omega} = 1.73\text{ mA}$$

$$r'_{e2} \cong \frac{25\text{ mV}}{I_{E2}} = \frac{25\text{ mV}}{17.3\text{ mV}} = \mathbf{14.5\ \Omega}$$

(d) $R_{in} = R_1 \parallel R_2 \parallel R_{in(base1)}$

$R_{in(base1)} = \beta_{ac1}\beta_{ac2}R_E = (150)(100)(1.5\text{ k}\Omega) = 22.5\text{ M}\Omega$

$R_{in} = 33\text{ k}\Omega \parallel 22\text{ k}\Omega \parallel 22.5\text{ M}\Omega = \mathbf{13.2\ k\Omega}$

27. $R_{in(base)} = \beta_{ac1}\beta_{ac2}R_E = (150)(100)(1.5\text{ k}\Omega) = 22.5\text{ M}\Omega$

$R_{in} = R_2 \parallel R_1 \parallel R_{in(base)} = 22\text{ k}\Omega \parallel 33\text{ k}\Omega \parallel 22.5\text{ M}\Omega = 13.2\text{ k}\Omega$

$$I_{in} = \frac{V_{in}}{R_{in}} = \frac{1\text{ V}}{13.2\text{ k}\Omega} = 75.8\ \mu\text{A}$$

$$I_{in(base1)} = \frac{V_{in}}{R_{in(base1)}} = \frac{1\text{ V}}{22.5\text{ M}\Omega} = 44.4\text{ nA}$$

$I_e \cong \beta_{ac1}\beta_{ac2}I_{in(base1)} = (150)(100)(44.4\text{ nA}) = 667\ \mu\text{A}$

$$A'_i = \frac{I_e}{I_{in}} = \frac{667\ \mu\text{A}}{75.8\ \mu\text{A}} = \mathbf{8.8}$$

Section 6-5 The Common-Base Amplifier

28. The main disadvantage of a common-base amplifier is **low input impedance**. Another disadvantage is **unity current gain**.

29. $$V_{\text{E}} = \left(\frac{R_2}{R_1 + R_2}\right)V_{\text{CC}} - V_{\text{BE}} = \left(\frac{10\text{ k}\Omega}{32\text{ k}\Omega}\right)24\text{ V} - 0.7\text{ V} = 6.8\text{ V}$$

$$I_{\text{E}} = \frac{6.8\text{ V}}{620\ \Omega} = 10.97\text{ mA}$$

$$R_{in(emitter)} = r_e' \cong \frac{25\text{ mV}}{I_{\text{E}}} = \frac{25\text{ mA}}{10.97\text{ mA}} = \mathbf{2.28\ \Omega}$$

$$A_v = \frac{R_C}{r_e'} = \frac{1.2\text{ k}\Omega}{2.28\ \Omega} = \mathbf{526}$$

$$A_i \cong \mathbf{1}$$

$$A_p = A_i A_v \cong \mathbf{526}$$

30. (a) Common-base (b) Common-emitter (c) Common-collector

Section 6-6 Multistage Amplifiers

31. $$A_v' = A_{v1}A_{v2} = (20)(20) = \mathbf{400}$$

32. $$A_{v(\text{dB})}' = 10\text{ dB} + 10\text{ dB} + 10\text{ dB} = \mathbf{30\ dB}$$

$$20\log A_v' = 30\text{ dB}$$

$$\log A_v' = \frac{30}{20} = 1.5$$

$$A_v' = \mathbf{31.6}$$

33. (a) $$V_{\text{E}}\left(\frac{R_2}{R_1 + R_2}\right)V_{\text{CC}} - V_{\text{BE}} = \left(\frac{8.2\text{ k}\Omega}{33\text{ k}\Omega + 8.2\text{ k}\Omega}\right)15\text{ V} - 0.7\text{ V} = 2.29\text{ V}$$

$$I_{\text{E}} = \frac{V_{\text{E}}}{R_{\text{E}}} = \frac{2.29\text{ V}}{1.0\text{ k}\Omega} = 2.29\text{ mA}$$

$$r_e' \cong \frac{25\text{ mV}}{I_{\text{E}}} = \frac{25\text{ mA}}{2.29\text{ mA}} = 10.9\ \Omega$$

$$R_{in(2)} = R_6 \parallel R_5 \parallel \beta_{ac}r_e' = 8.2\text{ k}\Omega \parallel 33\text{ k}\Omega \parallel 175(10.9\ \Omega) = 1.48\text{ k}\Omega$$

$$A_{v1} = \frac{R_{\text{C}} \parallel R_{in(2)}}{r_e'} = \frac{3.3\text{ k}\Omega \parallel 1.48\text{ k}\Omega}{10.9\ \Omega} = \mathbf{93.6}$$

$$A_{v2} = \frac{R_{\text{C}}}{r_e'} = \frac{3.3\text{k}\Omega}{10.9\Omega} = \mathbf{303}$$

(b) $A'_v = A_{v1}A_{v2} = (93.6)(303) = \mathbf{28{,}361}$

(c) $A_{v1(\text{dB})} = 20\log(93.6) = \mathbf{39.4\ dB}$

$A_{v2(\text{dB})} = 20\log(303) = \mathbf{49.6\ dB}$

$A'_{v(\text{dB})} = 20\log(28{,}361) = \mathbf{89.1\ dB}$

34. (a) $A_{v1} = \dfrac{R_C \parallel R_{in(2)}}{r'_e} = \dfrac{3.3\text{ k}\Omega \parallel 1.48\text{ k}\Omega}{10.9\ \Omega} = \mathbf{93.6}$

$$A_{v2} = \frac{R_C \parallel R_L}{r'_e} = \frac{3.3\text{ k}\Omega \parallel 18\text{ k}\Omega}{10.9\ \Omega} = \mathbf{256}$$

(b) $R_{in(1)} = R_1 \parallel R_2 \parallel \beta_{ac}r'_e = 33\text{ k}\Omega \parallel 8.2\text{ k}\Omega \parallel 175(10.9\ \Omega) = 1.48\text{ k}\Omega$

Attenuation of the input network is

$$\frac{R_{in(1)}}{R_{in(1)} + R_s} = \frac{1.48\text{ k}\Omega}{1.48\text{ k}\Omega + 75\ \Omega} = 0.95$$

$A'_v = (0.95)A_{v1}A_{v2} = (0.95)(93.6)(256) = \mathbf{22{,}764}$

(c) $A_{v1(\text{dB})} = 20\log(93.6) = \mathbf{39.4\ dB}$

$A_{v2(\text{dB})} = 20\log(256) = \mathbf{48.2\ dB}$

$A'_{v(\text{dB})} = 20\log(22{,}764) = \mathbf{87.1\ dB}$

35. $V_{B1} = \left(\dfrac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\dfrac{22\text{ k}\Omega}{122\text{ k}\Omega}\right)12\text{ V} = \mathbf{2.16\ V}$

$V_{E1} = V_{B1} - 0.7\text{ V} = \mathbf{1.46\ V}$

$$I_{C1} \cong I_{E1} = \frac{V_{E1}}{R_4} = \frac{1.46\text{ V}}{4.7\text{ k}\Omega} = 0.311\text{ mA}$$

$V_{C1} = V_{CC} - I_{C1}R_3 = 12\text{ V} - (0.311\text{ mA})(22\text{ k}\Omega) = \mathbf{5.16\ V}$

$V_{B2} = V_{C1} = \mathbf{5.16\ V}$

$V_{E2} = V_{B2} - 0.7\text{ V} = 5.16\text{ V} - 0.7\text{ V} = \mathbf{4.46\ V}$

$$I_{C2} \cong I_{E2} = \frac{V_{E2}}{R_6} = \frac{4.46\text{ V}}{10\text{ k}\Omega} = 0.446\text{ mA}$$

$V_{C2} = V_{CC} - I_{C2}R_5 = 12\text{ V} - (0.446\text{ mA})(10\text{ k}\Omega) = \mathbf{7.54\ V}$

$$r'_{e2} \cong \frac{25\text{ mV}}{I_{E2}} = \frac{25\text{ mV}}{0.446\text{ mA}} = 56\ \Omega$$

$$R_{in(2)} = \beta_{ac}r'_{e2} = (125)(56\ \Omega) = 7\text{ k}\Omega$$

$$r'_{e1} \cong \frac{25\text{ mV}}{I_{\text{E1}}} = \frac{25\text{ mV}}{0.311\text{ mA}} = 80.4\ \Omega$$

$$A_{v1} = \frac{R_3 \parallel R_{in(2)}}{r'_{e1}} = \frac{22\text{ k}\Omega \parallel 7\text{ k}\Omega}{80.4\ \Omega} = \mathbf{66}$$

$$A_{v2} = \frac{R_5}{r'_{e2}} = \frac{10\text{ k}\Omega}{56\ \Omega} = \mathbf{179}$$

$$A'_v = A_{v1}A_{v2} = (66)(179) = \mathbf{11{,}814}$$

36. (a) 20 log(12) = **21.6 dB**

(b) 20 log(50) = **34.0 dB**

(c) 20 log(100) = **40.0 dB**

(d) 20 log(2500) = **68.0 dB**

37. (a) $20\log\left(\frac{V_2}{V_1}\right) = 3\text{ dB}$

$\log\left(\frac{V_2}{V_1}\right) = \frac{3}{20} = 0.15$

$\frac{V_2}{V_1} = \mathbf{1.41}$

(b) $20\log\left(\frac{V_2}{V_1}\right) = 6\text{ dB}$

$\log\left(\frac{V_2}{V_1}\right) = \frac{6}{20} = 0.3$

$\frac{V_2}{V_1} = \mathbf{2}$

(c) $20\log\left(\frac{V_2}{V_1}\right) = 10\text{ dB}$

$\log\left(\frac{V_2}{V_1}\right) = \frac{10}{20} = 0.5$

$\frac{V_2}{V_1} = \mathbf{3.16}$

(d) $20\log\left(\frac{V_2}{V_1}\right) = 20\text{ dB}$

$\log\left(\frac{V_2}{V_1}\right) = \frac{20}{20} = 1$

$\frac{V_2}{V_1} = \mathbf{10}$

(e) $20\log\left(\frac{V_2}{V_1}\right) = 40\text{ dB}$

$\log\left(\frac{V_2}{V_1}\right) = \frac{40}{20} = 2$

$\frac{V_2}{V_1} = \mathbf{100}$

Chapter 6

Section 6-7 The Differential Amplifier

38. Determine I_E for each transistor:

$$I_{R_E} = \frac{V_{R_E}}{R_E} = \frac{14.3\text{ V}}{2.2\text{ k}\Omega} = 6.5\text{ mA}$$

$$I_{E(Q1)} = I_{E(Q2)} = \frac{I_{R_E}}{2} = 3.25\text{ mA}$$

Determine I_C for each transistor:

$I_{C(Q1)} = \alpha_1 I_{E(Q1)} = 0.980(3.25\text{ mA}) = 3.185\text{ mA}$

$I_{C(Q2)} = \alpha_2 I_{E(Q2)} = 0.975(3.25\text{ mA}) = 3.169\text{ mA}$

Calculate the collector voltages:

$V_{C(Q1)} = 15\text{ V} - (3.185\text{ mA})(3.3\text{ k}\Omega) = 4.49\text{ V}$

$V_{C(Q2)} = 15\text{ V} - (3.169\text{ mA})(3.3\text{ k}\Omega) = 4.54\text{ V}$

The differential output voltage is:

$V_{OUT} = V_{C(Q2)} - V_{C(Q1)} = 4.54\text{ V} - 4.49\text{ V} = 0.05\text{ V} = \mathbf{50\text{ mV}}$

39. V_1 measures the differential output voltage.

V_2 measures the noninverting input voltage.

V_3 measures the single-ended output voltage.

V_4 measures the differential input voltage.

I_1 measures the bias current.

40. Calculate the voltage across each collector resistor:

$V_{R_{C1}} = (1.35\text{ mA})(5.1\text{ k}\Omega) = 6.89\text{ V}$

$V_{R_{C2}} = (1.29\text{ mA})(5.1\text{ k}\Omega) = 6.58\text{ V}$

The differential output voltage is:

$$V_{OUT} = V_{C(Q2)} - V_{C(Q1)} = (V_{CC} - V_{R_{C2}}) - (V_{CC} - V_{R_{C1}}) = V_{R_{C1}} - V_{R_{C2}}$$

$$= 6.89\text{ V} - 6.58\text{ V} = 0.31\text{ V} = \mathbf{310\text{ mV}}$$

41. (a) Single-ended differential input, differential output

(b) Single-ended, differential input, single-ended output

(c) Double-ended differential input, single-ended output

(d) Double-ended differential input, differential output

Section 6-8 Troubleshooting

42. $$V_E = \left(\frac{R_1}{R_1 + R_2}\right)10\text{ V} - 0.7\text{ V} = \left(\frac{10\text{ k}\Omega}{57\text{ k}\Omega}\right)10\text{ V} - 0.7\text{ V} = 1.05\text{ V}$$

$$I_E = \frac{V_E}{R_4} = \frac{1.05\text{ V}}{1.0\text{ k}\Omega} = 1.05\text{ mA}$$

$V_C = 10\text{ V} - (1.05\text{ mA})(4.7\text{ k}\Omega) = 5.07\text{ V}$

$V_{CE} = 5.07\text{ V} - 1.05\text{ V} = 4.02\text{ V}$

$$r'_{CE} \cong \frac{V_{CE}}{I_E} = \frac{4.02\text{ V}}{1.05\text{ mA}} = 3.83\text{ k}\Omega$$

With C_2 shorted:

$$R_{IN(2)} = R_6 \parallel \beta_{DC}R_8 = 10\text{ k}\Omega \parallel 125(1.0\text{ k}\Omega) = 9.26\text{ k}\Omega$$

Looking from the collector of Q_1:

$$(r'_{CE} + R_4) \parallel R_{IN(2)} = (3.83\text{ k}\Omega + 1.0\text{ k}\Omega) \parallel 9.26\text{ k}\Omega = 3.17\text{ k}\Omega$$

$$V_{C1} = \left(\frac{3.17\text{ k}\Omega}{3.17\text{ k}\Omega + 4.7\text{ k}\Omega}\right)10\text{ V} = \mathbf{4.03\text{ V}}$$

43. Q_1 is in **cutoff**. $I_C = 0$ A, so $V_{C2} =$ **10 V**.

44. (a) Reduced gain
(b) No output signal
(c) Reduced gain
(d) Bias levels of first stage will change. I_C will increase and Q_1 will go into saturation.
(e) No signal at the Q_1 collector
(f) Signal at the Q_2 base. No output signal.

45. $r'_e = 10.9\ \Omega$ $\qquad R_{in} = 1.48\text{ k}\Omega$

$A_{v1} = 93.6$ $\qquad A_{v2} = 302$

Test Point	**DC Volts**	**AC Volts (rms)**
Input	0 V	25 μA
Q_1 base	2.99 V	20.8 μV
Q_1 emitter	2.29 V	0 V
Q_1 collector	7.44 V	1.95 mV
Q_2 base	2.99 V	1.95 mV
Q_2 emitter	2.29 V	0 V
Q_2 collector	7.44 V	589 mV
Output	0 V	589 mV

Chapter 6

Device Application Problems

46. For the block diagram of textbook Figure 6-47 with no output from the power amplifier or preamplifier and only one faulty block, the power amplifier must be ok because the fault must be one that affects the preamplifier's output prior to the power amplifier. Check the input to the preamplifier.

47. (a) No output signal

(b) Reduced output signal

(c) No output signal

(d) Reduced output signal

(e) No output signal

(f) Increased output signal (perhaps with distortion)

48. $R_7 = 220\ \Omega$ will bias Q_2 off.

49. (a) Q_1 is in **cutoff**.

(b) $V_{C1} = V_{\text{EE}}$

(c) V_{C2} is unchanged and at **5.87 V**.

Datasheet Problems

50. From the datasheet in textbook Figure 6-64:

(a) For a 2N3947, $\beta_{ac(\min)} = h_{fe(\min)} = \mathbf{100}$

(b) For a 2N3947, $r'_{e(\min)}$ cannot be determined since $h_{re(\min)}$ is not given.

(c) For a 2N3947, $r'_{c(\min)}$ cannot be determined since $h_{re(\min)}$ is not given.

51. From the 2N3947 datasheet in Figure 6-64:

(a) For a 2N3947, $\beta_{ac(\max)} = \mathbf{700}$

(b) For a 2N3947, $r'_{e(\max)} = \dfrac{h_{re}}{h_{oe}} = \dfrac{20\times 10^{-4}}{50\,\mu\text{S}} = \mathbf{40\,\Omega}$

(c) For a 2N3947, $r'_{e(\max)} = \dfrac{h_{re}+1}{h_{oe}} = \dfrac{20\times 10^{-4}+1}{50\,\mu\text{S}} = \mathbf{20\,k\Omega}$

52. For maximum current gain, a **2N3947** should be used.

Advanced Problems

53. In the circuit of textbook Figure 6-63, a leaky coupling capacitor would affect the biasing of the transistors, attenuate the ac signal, and decrease the frequency response.

54. See Figure 6-3.

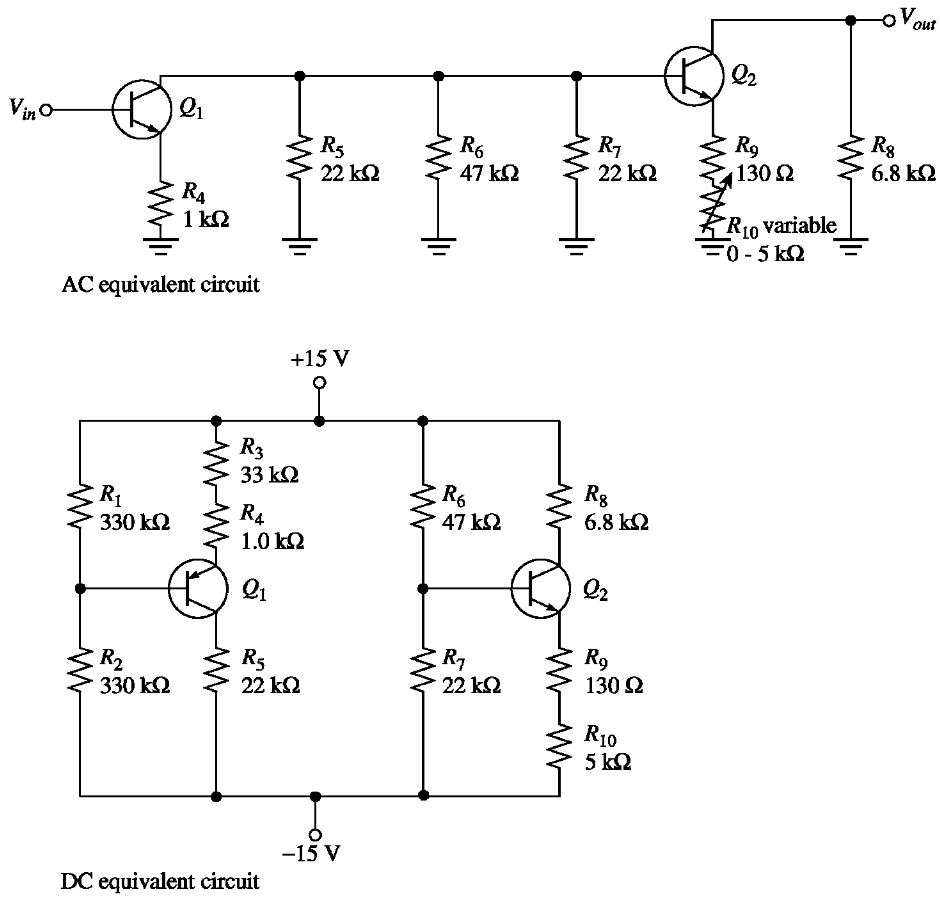

Figure 6-3

55. For the 2nd stage:

$$I_{R6-7} = \frac{30\text{ V}}{R_6 + R_7} = \frac{30\text{ V}}{69\text{ k}\Omega} = 435\ \mu\text{A}$$

$$V_{B2} = V_{CC} - I_{R6\text{-}7}R_6 = 15\text{ V} - (435\ \mu\text{A})(47\text{ k}\Omega)$$
$$= 15\text{ V} - 20.5\text{ V} = -5.5\text{ V}$$

$$I_{E2} = \frac{V_{E2}}{R_9 + R_{10}} = \frac{-5.5\text{ V} - 0.7\text{ V}}{5.13\text{ k}\Omega} = -1.21\text{ mA}$$

$$r'_{e2} = \frac{25\text{ mA}}{1.21\text{ mA}} = 20.7\ \Omega$$

With $R_{10} = 0\ \Omega$ for max gain:

$$A_{v(2)} = \frac{R_8}{R_9 + r'_{e2}} = \frac{6.8\ \text{k}\Omega}{150.7\ \Omega} = 45.1\ \text{(unloaded)}$$

With a 10 kΩ load:

$$A_{v(2)} = \frac{R_8 \parallel R_L}{R_9 + r'_{e2}} = \frac{6.8\ \text{k}\Omega \parallel 10\ \text{k}\Omega}{150.7\ \Omega} = \frac{4.05\ \text{k}\Omega}{150.7\ \Omega} = 26.9$$

To keep unloaded gain:

$$\frac{4.05\ \text{k}\Omega}{R_9 + 20.7\ \Omega} = 45.1$$

$4.05\ \text{k}\Omega = 45.1(R_9 + 20.7\ \Omega) = 45.1R_9 + 934\ \Omega$

$$R_9 = \frac{4.05\ \text{k}\Omega - 934\ \Omega}{45.1} = \mathbf{69.1\ \Omega}$$

56. $R_C > (100)(330\ \Omega) = 33\ \text{k}\Omega$

To prevent cutoff, V_C must be no greater than

$12\ \text{V} - (100)(1.414)(25\ \text{mV}) = 8.46\ \text{V}$

In addition, V_C must fall no lower than $8.46\ \text{V} - 3.54\ \text{V} = 4.93\ \text{V}$ to prevent saturation.

$$R_C = 100(R_E + r'_e)$$

$$r'_e = \frac{25\ \text{mV}}{I_E}$$

$12\ \text{V} - I_C R_C = 8.46\ \text{V}$

$I_C R_C = 3.54\ \text{V}$

$$I_C(100(R_E + r'_e)) = 3.54\ \text{V}$$

$$I_C\left(100\left(330\ \Omega + \frac{25\ \text{mV}}{I_C}\right)\right) \cong 3.54\ \text{V}$$

$(33\ \text{k}\Omega)I_C + 2.5\ \text{V} = 3.54\ \text{V}$

$I_C = 31.4\ \mu\text{A}$

$$r'_e \cong \frac{25\ \text{mV}}{31.4\ \mu\text{A}} = 797\ \Omega$$

$R_C = 100(330\ \Omega + 797\ \Omega) = 113\ \text{k}\Omega$

Let $R_C = 120\ \text{k}\Omega$.

$V_C = 12\ \text{V} - (31.4\ \mu\text{A})(120\ \text{k}\Omega) = 8.23\ \text{V}$

$V_{C(sat)} = 8.23\ \text{V} - 3.54\ \text{V} = 4.69\ \text{V}$

$$\frac{R_{E(tot)}}{R_C} = \frac{4.69\text{ V}}{7.31\text{ V}}$$

$R_{E(tot)} = (0.642)(120\text{ k}\Omega) = 77\text{ k}\Omega$. Let $R_E = 68\text{ k}\Omega$.

$V_E = (31.4\ \mu\text{A})(68\text{ k}\Omega) = 2.14\text{ V}$

$V_B = 2.14\text{ V} + 0.7\text{ V} = 2.84\text{ V}$

$$\frac{R_2}{R_1} = \frac{2.84\text{ V}}{9.16\text{ V}} = 0.310$$

$R_2 = 0.310R_1$. If $R_1 = 20\text{ k}\Omega$, $R_2 = 6.2\text{ k}\Omega$.

The amplifier circuit is shown in Figure 6-4.

From the design:

$$V_B = \left(\frac{6.2\text{ k}\Omega}{26.2\text{ k}\Omega}\right)12\text{ V} = 2.84\text{ V}$$

$V_E = 2.14\text{ V}$

$$I_C \cong I_E = \frac{2.14\text{ V}}{68.3\text{ k}\Omega} = 31.3\ \mu\text{A}$$

$$r_e' = \frac{25\text{ mV}}{31.3\ \mu\text{A}} = 798\ \Omega$$

$$A_v = \frac{120\text{ k}\Omega}{795\ \Omega + 330\ \Omega} = 106 \text{ or } 40.5\text{ dB}$$

$V_C = 12\text{ V} - (31.3\ \mu\text{A})(120\text{ k}\Omega) = 8.24\text{ V}$

The design is a close fit.

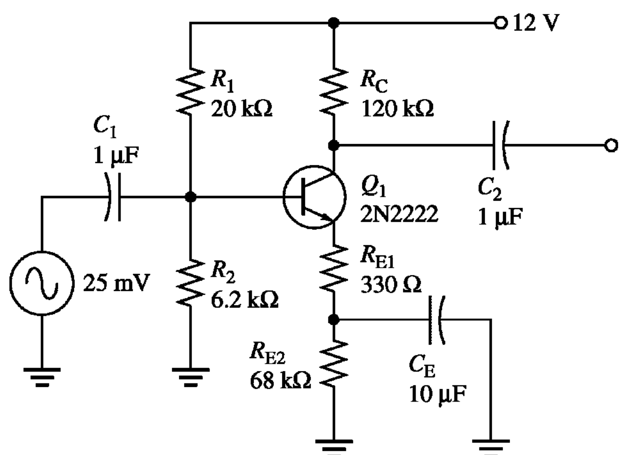

Figure 6-4

57. See Figure 6-5.

$R_{in} = 120\ \text{k}\Omega \,\|\, 120\ \text{k}\Omega \,\|\, (100)(5.1\ \text{k}\Omega) = 53.6\ \text{k}\Omega$ minimum

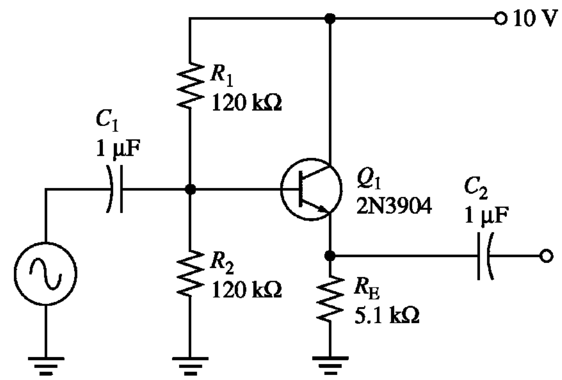

Figure 6-5

58. See Figure 6-6.

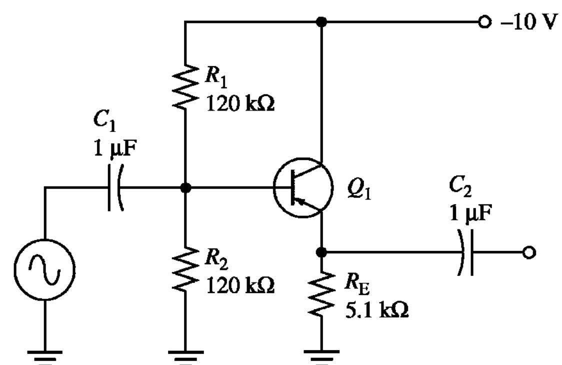

Figure 6-6

59. See Figure 6-7.

$$I_C = \frac{6\ \text{V} - 0.7\ \text{V}}{510\ \Omega + 2\ \text{k}\Omega/100} = 10\ \text{mA}$$

$$r_e' = \frac{25\ \text{mA}}{10\ \text{mA}} = 2.5\ \Omega$$

$$A_v = \frac{180\ \Omega}{2.5\ \Omega} = 72.4$$

This is reasonably close (≈3.3% off) and can be made closer by putting a 7.5 Ω resistor in series with the 180 Ω collector resistor.

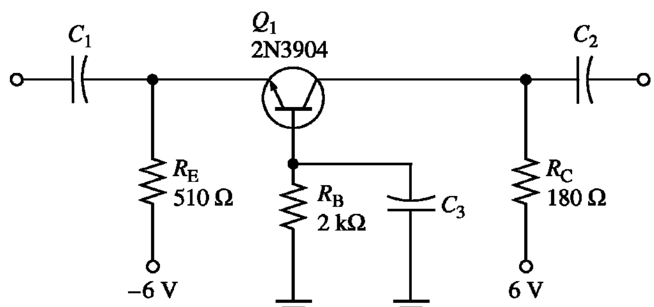

Figure 6-7

60. Assuming $\beta_{ac} = 200$,

$$C_1 = \frac{1}{2\pi f_c R} = \frac{1}{2\pi(100\text{ Hz})(330\text{ k}\Omega \parallel 330\text{ k}\Omega \parallel (200\times 34\text{ k}\Omega))}$$

$$= \frac{1}{2\pi(100\text{ Hz})(161\text{ k}\Omega)} = \mathbf{0.01\ \mu F}$$

$$C_2 = \frac{1}{2\pi f_c R} = \frac{1}{2\pi(100\text{ Hz})(22\text{ k}\Omega + 47\text{ k}\Omega \parallel 22\text{ k}\Omega \parallel (200\times 5.13\text{ k}\Omega))}$$

$$= \frac{1}{2\pi(100\text{ Hz})(36.98\text{ k}\Omega)} = \mathbf{0.043\ \mu F}$$

61. $I_\text{C} \cong I_\text{E}$

$$A_v = \frac{R_\text{C}}{r'_e} \cong \frac{R_\text{C}}{25\text{ mV}/I_\text{E}} \cong \frac{R_\text{C}}{25\text{ mV}/I_\text{C}} = \frac{R_\text{C} I_\text{C}}{25\text{ mV}} = \frac{V_{\text{R}_\text{C}}}{25\text{ mV}} = 40\, V_{\text{R}_C}$$

Multisim Troubleshooting Problems

62. C_2 open

63. C_2 shorted

64. R_E leaky

65. C_1 open

66. C_2 open

67. C_3 open

Chapter 7
BJT Power Amplifiers

Section 7-1 The Class A Power Amplifier

1. (a) $V_B = \left(\dfrac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\dfrac{330\ \Omega}{1.0\ \text{k}\Omega + 330\ \text{k}\Omega}\right)15\ \text{V} = 3.72\ \text{V}$

$V_E = V_B - V_{BE} = 3.72 - 0.7\ \text{V} = 3.02\ \text{V}$

$I_{CQ} \cong I_E = \dfrac{V_E}{R_{E1} + R_{E2}} = \dfrac{3.02\ \text{V}}{8.2\ \Omega + 36\ \Omega} = \mathbf{68.4\ mA}$

$V_{CEQ} = V_{CC} - (I_C)(R_{E1} + R_{E2} + R_L) = 15\ \text{V} - (68.4\ \text{mA})(8.2\ \Omega + 36\ \Omega + 100\ \Omega)$
$= \mathbf{5.14\ V}$

(b) $A_v = \dfrac{R_L}{R_{E1} + r'_e} = \dfrac{100\ \Omega}{8.2\ \Omega + 0.3\ \Omega} = \mathbf{11.7}$

$R_{in} = \beta_{ac}(R_{E1} + r'_e) \parallel R_1 \parallel R_2$
$= 100(8.2\ \Omega + 0.37\ \Omega) \parallel 330\ \Omega \parallel 1.0\ \text{k}\Omega = 192\ \Omega$

$A_p = A_v^2\left(\dfrac{R_{in}}{R_L}\right) = 11.7^2\left(\dfrac{192\ \Omega}{100\ \Omega}\right) = \mathbf{263}$

The computed voltage and power gains are slightly higher if r'_e is ignored.

2. (a) If R_L is removed, there is no collector current; hence, the power dissipated in the transistor is **zero**.

(b) Power is dissipated only in the bias resistors plus a small amount in R_{E1} and R_{E2}. Since the load resistor has been removed, the base voltage is altered. The base voltage can be found from the Thevenin equivalent drawn for the bias circuit in Figure 7-1.

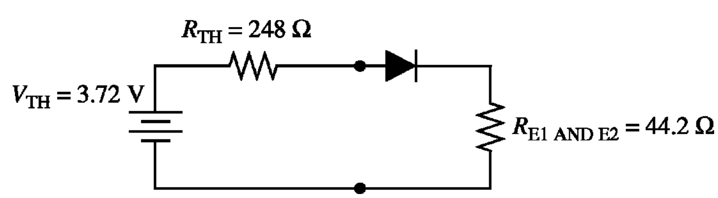

Figure 7-1

Applying the voltage-divider rule and including the base-emitter diode drop of 0.7 V result in a base voltage of 1.2 V. The power supply current is then computed as

$$I_{CC} = \frac{V_{CC} - 1.2\text{ V}}{R_1} = \frac{15\text{ V} - 1.2\text{ V}}{1.0\text{ k}\Omega} = 13.8\text{ mA}$$

Power from the supply is then computed as

$$P_T = I_{CC}V_{CC} = (13.8\text{ mA})(15\text{ V}) = \mathbf{207\ mW}$$

(c) $A_v = 11.7$ (see problem 1(b)). $V_{in} = 500\text{ mV}_{pp} = 177\text{ mV}_{rms}$.

$$V_{out} = A_v V_{in} = (11.7)(177\text{ mV}) = 2.07\text{ V}$$

$$P_{out} = \frac{V_{out}^2}{R_L} = \frac{2.07\text{ V}^2}{100\ \Omega} = \mathbf{42.8\ mW}$$

3. The changes are shown in Figure 7-2. The advantage of this arrangement is that the load resistor is referenced to ground.

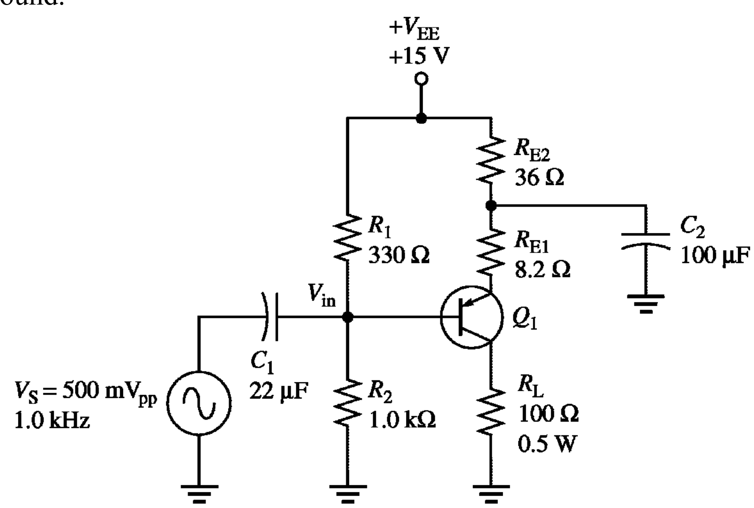

Figure 7-2

4. A CC amplifier has a voltage gain of approximately 1. Therefore,

$$A_p = \frac{R_{in}}{R_{out}} = \frac{2.2\text{ k}\Omega}{50\ \Omega} = \mathbf{44}$$

5. (a) $V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{510\ \Omega}{1190\ \Omega}\right)12\text{ V} = 5.14\text{ V}$

$$R_{TH} = \left(\frac{R_1 R_2}{R_1 + R_2}\right) = \frac{(680\ \Omega)(510\ \Omega)}{1190\ \Omega} = 291\ \Omega$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{5.14\text{ V} - 0.7\text{ V}}{79.7\ \Omega + 291\ \Omega/125} = 54\text{ mA}$$

$$I_C \cong I_E = \mathbf{54\ mA}$$

$$V_C = V_{CC} - I_C R_C = 12\text{ V} - (54\text{ mA})(100\ \Omega) = 6.6\text{ V}$$

$$V_E = I_E R_E = (54\text{ mA})(79.7\ \Omega) = 4.3\text{ V}$$

$$V_{CE} = V_C - V_E = 6.6\text{ V} - 4.3\text{ V} = \mathbf{2.3\ V}$$

(b) $$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{4.7\text{ k}\Omega}{16.7\text{ k}\Omega}\right)12\text{ V} = 3.38\text{ V}$$

$$R_{TH} = \left(\frac{R_1 R_2}{R_1 + R_2}\right) = \frac{(12\text{ k}\Omega)(4.7\text{ k}\Omega)}{16.7\text{ k}\Omega} = 3.38\text{ k}\Omega$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{3.38\text{ V} - 0.7\text{ V}}{142\ \Omega + 3.38\text{ k}\Omega/120} = 15.7\text{ mA}$$

$$I_C \cong I_E = \mathbf{15.7\ mA}$$

$$V_C = V_{CC} - I_C R_C = 12\text{ V} - (15.7\text{ mA})(470\ \Omega) = 4.62\text{ V}$$

$$V_E = I_E R_E = (15.7\text{ mA})(142\ \Omega) = 2.23\text{ V}$$

$$V_{CE} = V_C - V_E = 4.62\text{ V} - 2.23\text{ V} = \mathbf{2.39\ V}$$

6. The Q-point does not change because R_L is capacitively coupled and does not affect the DC values.

7. For the circuit in Figure 7-42(a):

From Problem 5(a),

$$I_{CQ} = 54\text{ mA};\ V_{CEQ} = 2.3\text{ V}$$

$$R_e = R_C \parallel R_L = 100\ \Omega \parallel 100\ \Omega = 50\ \Omega$$

$$V_{ce(cutoff)} = V_{CEQ} + I_{CQ}R_c = 2.3\text{ V} + (54\text{ mA}(50\ \Omega) = 5\text{ V}$$

Since V_{CEQ} is closer to saturation, I_c is limited to

$$I_{c(p)} = \frac{V_{CEQ}}{R_c} = \frac{2.3\text{ V}}{50\ \Omega} = \mathbf{46\ mA}$$

V_{out} is limited to

$$V_{out(p)} = V_{CEQ} = \mathbf{2.3\ V}$$

For the circuit in Figure 7-43(b):

From Problem 5(b),

$$I_{CQ} = 15.7\text{ mA};\quad V_{CEQ} = 2.39\text{ V}$$

$$R_e = R_C \parallel R_L = 470\ \Omega \parallel 470\ \Omega = 235\ \Omega$$

$$V_{ce(cutoff)} = V_{CEQ} + I_{CQ}R_c = 2.39\text{ V} + (15.7\text{ mA})(235\ \Omega) = 6.08\text{ V}$$

Since V_{CEQ} is closer to saturation, I_c is limited to

$$I_{c(p)} = \frac{V_{\text{CEQ}}}{R_c} = \frac{2.39\text{ V}}{235\ \Omega} = \mathbf{10.2\ mA}$$

V_{out} is limited to

$$V_{\text{out}(p)} = V_{\text{CEQ}} = \mathbf{2.39\ V}$$

8. (a) $A_p = A_v^2\left(\dfrac{R_{in}}{R_L}\right)$

$$A_v \cong \frac{R_c}{R_{\text{E1}}} = \frac{R_{\text{C}} \parallel R_L}{R_{\text{E1}}} = \frac{100\ \Omega \parallel 100\ \Omega}{4.7\ \Omega} = \frac{50\ \Omega}{4.7\ \Omega} = \mathbf{10.6}$$

$$R_{in} = R_1 \parallel R_2 \parallel R_{in(base)} = R_1 \parallel R_2 \parallel \beta_{ac} R_{\text{E1}}$$

$$R_{in} = 680\ \Omega \parallel 510\ \Omega \parallel (125)(4.7\ \Omega) = 680\ \Omega \parallel 510\ \Omega \parallel 588\ \Omega = 195\ \Omega$$

$$A_p = (10.6)^2\left(\frac{195\ \Omega}{100\ \Omega}\right) = \mathbf{219}$$

(b) $$A_v \cong \frac{R_c}{R_{\text{E1}}} = \frac{R_C \parallel R_L}{R_{\text{E1}}} = \frac{470\ \Omega \parallel 470\ \Omega}{22\ \Omega} = \frac{235\ \Omega}{22\ \Omega} = \mathbf{10.7}$$

$$R_{in} = 12\text{ k}\Omega \parallel 4.7\text{ k}\Omega \parallel (120)(22\ \Omega) = 12\text{ k}\Omega \parallel 4.7\text{ k}\Omega \parallel 2.64\text{ k}\Omega = 1.48\text{ k}\Omega$$

$$A_p = (10.7)^2\left(\frac{1.48\text{ k}\Omega}{470\ \Omega}\right) = \mathbf{361}$$

9. $$V_{\text{B}} = \frac{R_2 \parallel \beta_{\text{DC}}(R_{\text{E1}} + R_{\text{E2}})V_{\text{CC}}}{(\text{R}_1 + R_2 \parallel \beta_{\text{DC}}(R_{\text{E1}} + R_{\text{E2}})}$$

$$= \frac{1.0\text{ k}\Omega \parallel 100(130\text{ k}\Omega)\,24\text{ V}}{4.7\text{ k}\Omega + 1\text{ k}\Omega \parallel 100(130\text{ k}\Omega = 4.2\text{ V}}$$

$$V_{\text{E}} = V_{\text{B}} - 0.7\text{ V} = 4.2 - 0.7\text{ V} = 3.5\text{ V}$$

$$\frac{I_{\text{C}} = I_{\text{E}} = V_{\text{E}}}{(R_{\text{E1}} + R_{\text{E2}})} = \frac{3.5\text{ V}}{130\ \Omega} = 26.9\text{ mA}$$

$$V_{\text{C}} = V_{\text{CC}} - I_{\text{CRC}} = 24\text{ V} - (26.9\text{ mA})(560\ \Omega) = 8.94\text{ V}$$

$$V_{\text{CE}} = V_{\text{C}} - V_{\text{E}} = 8.94\text{ V} - 3.5\text{ V} = 5.44\text{ V}$$

10. $$A_v = \frac{R_{\text{C}}}{re' + R_{\text{E1}}} = \frac{560\ \Omega}{20\ \Omega} = 28$$

11. $$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{1\text{ k}\Omega}{5.7\text{ k}\Omega}\right)24\text{ V} = 4.2\text{ V}$$

$$R_{TH} = \frac{R_1R_2}{R_1 + R_2} = \frac{(4.7\text{ k}\Omega)(1\text{ k}\Omega)}{5.7\text{ k}\Omega} = 825\ \Omega$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{4.2\text{ V} - 0.7\text{ V}}{130\ \Omega + 825\ \Omega/90} = 25\text{ mA}$$

$$I_C \cong I_E = 25\text{ mA}$$

$$V_C = V_{CC} - I_CR_C = 24\text{ V} - (25\text{ mA})(560\ \Omega) = 10\text{ V}$$

$$V_E = I_ER_E = (25\text{ mA})(130\ \Omega) = 3.25\text{ V}$$

$$V_{CEQ} = V_C - V_E = 10\text{ V} - 3.25\text{ V} = 6.75\text{ V}$$

$$P_{D(\min)} = P_{DQ} = I_{CQ}V_{CEQ} = (25\text{ mA})(6.75\text{ V}) = \mathbf{169\ mW}$$

12. From Problem 9: $I_{CQ} = 25\text{ mA}$ and $V_{CEQ} = 6.75\text{ V}$

$$V_{ce(cutoff)} = V_{CEQ} + I_{CQ}R_c = 6.75\text{ V} + (25\text{ mA})(264\ \Omega) = 13.5\text{ V}$$

$$P_{out} = 0.5I_{CQ}^2R_c = 0.5(25\text{ mA})^2(264\ \Omega) = \mathbf{82.5\ mW}$$

$$\eta = \frac{P_{out}}{P_{DC}} = \frac{P_{out}}{V_{CC}I_{CC}} = \frac{P_{out}}{V_{CC}I_{CQ}} = \frac{82.5\text{ mW}}{(24\text{ V})(25\text{ mA})} = \mathbf{0.138}$$

Section 7-2 The Class B and Class AB Push-Pull Amplifiers

13. (a) $$V_{B(Q1)} = 0\text{ V} + 0.7\text{ V} = \mathbf{0.7\ V}$$

$$V_{B(Q2)} = 0\text{ V} - 0.7\text{ V} = \mathbf{-0.7\ V}$$

$$I_{CQ} = \frac{V_{CC} - (-V_{CC}) - 1.4\text{ V}}{R_1 + R_2} = \frac{9\text{ V} - (-9\text{ V}) - 1.4\text{ V}}{1.0\text{ k}\Omega + 1.0\text{ k}\Omega} = \mathbf{8.3\ mA}$$

$$V_{CEQ(Q1)} = \mathbf{9\ V}$$

$$V_{CEQ(Q2)} = \mathbf{-9\ V}$$

(b) $$V_{out} = V_{in} = 5.0\text{ V rms}$$

$$P_{out} = \frac{(V_{out})^2}{R_L} = \frac{5.0\text{ V}^2}{50\ \Omega} = \mathbf{0.5\ W}$$

14. $I_{c(sat)} = \dfrac{V_{CC}}{R_L} = \dfrac{9.0\text{ V}}{50\ \Omega} = 180\text{ mA}$

$V_{ce(cutoff)} = 9\text{ V}$

These points define the ac load line as shown in Figure 7-3. The Q-point is at a collector current of 8.3 mA (see problem 13) and the dc load line rises vertically through this point.

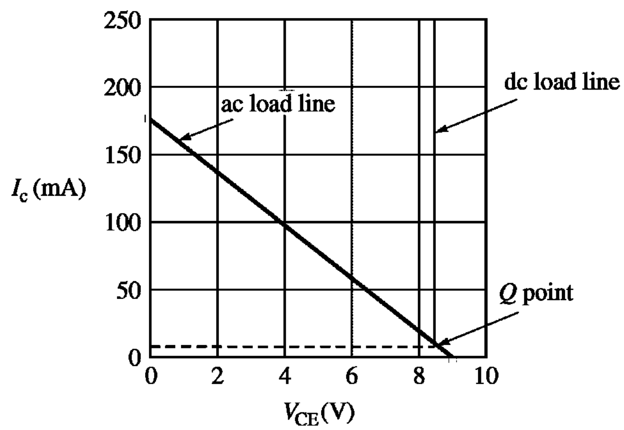

Figure 7-3

15. $R_{in} = \beta_{ac}(r'_e + R_L)R_1 \parallel R_2$

From Problem 11,

$I_{CQ} = 8.3\text{ mA}$

so, $I_E \cong 8.3\text{ mA}$

$r'_e = \dfrac{25\text{ mV}}{8.3\text{ mA}} = 3\ \Omega$

$R_{in} = 100(53\ \Omega \parallel 1.0\text{ k}\Omega \parallel 1.0\text{ k}\Omega$
$\quad = 5300\ \Omega \parallel 1.0\text{ k}\Omega \parallel 1.0\text{ k}\Omega = \mathbf{457\ \Omega}$

16. The DC voltage at the output becomes negative instead of 0 V.

17. (a) $V_{B(Q1)} = 7.5\text{ V} + 0.7\text{ V} = \mathbf{8.2\text{ V}}$

$V_{B(Q2)} = 7.5\text{ V} - 0.7\text{ V} = 6.8\text{ }\mathbf{V}$

$V_E = \dfrac{15\text{ V}}{2} = \mathbf{7.5\text{ V}}$

$I_{CQ} = \dfrac{V_{CC} - 1.4\text{ V}}{R_1 + R_2} = \dfrac{15\text{ V} - 1.4\text{ V}}{1.0\text{ k}\Omega + 1.0\text{ k}\Omega} = \mathbf{6.8\text{ mA}}$

$V_{CEQ(Q1)} = 15\text{ V} - 7.5\text{ V} = \mathbf{7.5\text{ V}}$

$V_{CEQ(Q2)} = 0\text{ V} - 7.5\text{ V} = \mathbf{-7.5\text{ V}}$

(b) $V_{in} = V_{out} = 10\ \text{V}_{\text{pp}} = 3.54\ \text{V rms}$

$$P_{\text{L}} = \frac{(V_{\text{L}})^2}{R_{\text{L}}} = \frac{(3.54\ \text{V})^2}{75\ \Omega} = \mathbf{167\ mW}$$

18. (a) Maximum peak voltage = 7.5 V_{p}. $7.5\ \text{V}_{\text{p}} = 5.30\ \text{V rms}$

$$P_{\text{L(max)}} = \frac{(V_{\text{L}})^2}{R_{\text{L}}} = \frac{(5.30\ \text{V})^2}{75\ \Omega} = \mathbf{375\ mW}$$

(b) Maximum peak voltage = 12 V_{p}. $12\ \text{V}_{\text{p}} = 8.48\ \text{V rms}$

$$P_{\text{L(max)}} = \frac{(V_{\text{L}})^2}{R_{\text{L}}} = \frac{(8.48\ \text{V})^2}{75\ \Omega} = \mathbf{960\ mW}$$

19. (a) C_2 open or Q_2 open

(b) power supply off, open R_1, Q_1 base shorted to ground

(c) Q_1 has collector-to-emitter short

(d) one or both diodes shorted

20. $R_{in} = \beta_{ac}(r'_e + R_L)R_1 \parallel R_2$

From Problem 15:

$I_{\text{CQ}} = 6.8\ \text{mA}$

$I_{\text{E}} \cong 6.8\ \text{mA}$

$$r'_e = \frac{25\ \text{mV}}{I_{\text{E}}} = \frac{25\ \text{mV}}{6.8\ \text{mA}} 3.68\ \Omega$$

$$R_{in} = 200(78.7\ \Omega) \parallel 1\ \text{k}\Omega \parallel 1\ \text{k}\Omega = 485\ \Omega$$

$$V_b\left(\frac{485\ \Omega}{485\ \Omega + 50\ \Omega}\right)1\ \text{V} = \mathbf{0.91\ V\ rms}$$

Section 7-3 The Class C Amplifier

21. $$P_{\text{D(avg)}} = \left(\frac{t_{on}}{T}\right)V_{\text{CE(sat)}}I_{\text{C(sat)}} = (0.1)(0.18\ \text{V})(25\ \text{mA}) = \mathbf{450\ \mu W}$$

22. $$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(10\ \text{mH})(0.001\ \mu\text{F})}} = \mathbf{50.3\ kHz}$$

23. $$V_{out(pp)} = 2V_{\text{CC}} = 2(12\ \text{V}) = \mathbf{24\ V}$$

24. $$P_{out} = \frac{0.5\,V_{CC}^2}{R_c} = \frac{0.5(15\text{ V})^2}{50\ \Omega} = 2.25\text{ W}$$

$$P_{D(avg)} = \left(\frac{t_{on}}{T}\right)V_{CE(sat)}I_{C(sat)} = (0.1)(0.18\text{ V})(25\text{ mA}) = 0.45\text{ mW}$$

$$\eta = \frac{P_{out}}{P_{out} + P_{D(avg)}} = \frac{2.25\text{ W}}{2.25\text{ W} + 0.45\text{ mW}} = \mathbf{0.9998}$$

Section 7-4 Troubleshooting

25. With C_1 open, only the negative half of the input signal appears across R_L.

26. One of the transistors is open between the collector and emitter or a coupling capacitor is open.

27. (a) No dc supply voltage or R_1 open
(b) Diode D_2 open
(c) Circuit is OK
(d) Q_1 shorted from collector to emitter

Device Application Problems

28. For the block diagram of textbook Figure 7-33 with no signal from the power amplifier or preamplifier, but with the microphone working, the problem is in the power amplifier or preamplifier. It must be assumed that the preamp is faulty, causing the power amp to have no signal.

29. For the circuit of Figure 7-34 with the base-emitter junction of Q_2 open, the dc output will be approximately –15 V with a signal output approximately equal to the input.

30. For the circuit of text Figure 7-34 with the collector-emitter junction of Q_5 open, the dc output will be approximately +15 V with a signal output approximately equal to the input (some distortion possible).

31. On the circuit board of text Figure 7-48, the vertically oriented diode has been installed backwards.

Datasheet Problems

32. From the BD135 datasheet of textbook Figure 7-49:

(a) $\beta_{DC(min)} = \mathbf{40}$ @ $I_C = 150\text{ mA}, V_{CE} = 2\text{ V}$
$\beta_{DC(min)} = \mathbf{25}$ @ $I_C = 5\text{ mA}, V_{CE} = 2\text{ V}$

(b) For a BD135, $V_{CE(max)} = V_{CEO} = \mathbf{45\ V}$

(c) $P_{D(max)} = \mathbf{12.5\ W}$ @ $T_C = 25°\text{C}$

(d) $I_{C(max)} = 1.5\text{ A}$

33. P_D = **10 W** @ 50ºC from graph in Figure 7-49.

34. P_D = 1 W @ 50ºC. Extrapolating from the case temperature graph in text Figure 7-49, since P_D = 1.25 W @ 25ºC ambient. This derating gives 1 W.

35. As I_C increases from 10 mA to approximately 125 mA, the dc current gain increases. As I_C increases above approximately 125 mA, the dc current gain decreases.

36. $h_{FE} \cong 89 \text{ @ } I_C = 20\text{ mA}$

Advanced Problems

37. T_C is much closer to the actual junction temperature than T_A. In a given operating environment, T_A is always less than T_C.

38. $$I_{C(\text{sat})} = \frac{24\text{ V}}{330\ \Omega + 100\ \Omega} = \frac{24\text{ V}}{430\ \Omega} = \mathbf{55.8\ mA}$$

$V_{CE(\text{cutoff})}$ = **24 V**

$$V_{BQ} = \left(\frac{1.0\text{ k}\Omega}{1.0\text{ k}\Omega + 4.7\text{ k}\Omega}\right)24\text{ V} = 4.21\text{ V}$$

V_{EQ} = 4.21 V – 0.7 V = 3.51 V

$$I_{EQ} \cong I_{CQ} = \frac{3.51\text{ V}}{100\ \Omega} = 35.1\text{ mA}$$

$$R_c = 330\ \Omega \parallel 330\ \Omega = 165\ \Omega$$

V_{CQ} = 24 V – (35.1 mA)(330 Ω) = 12.4 V

V_{CEQ} = 12.4 V – 3.51 V = 8.90 V

$$I_{c(\text{sat})} = 35.1\text{ mA} + \frac{8.90\text{ V}}{165\ \Omega} = \mathbf{89.1\ mA}$$

$V_{ce(\text{cutoff})}$ = 8.90 V + (35.1 mA)(165 Ω) = **14.7 V**

See Figure 7-4.

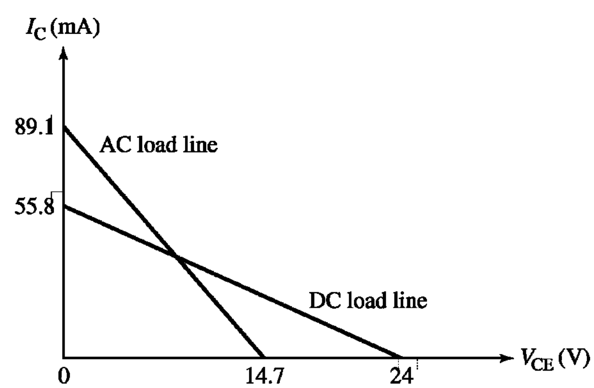

Figure 7-4

39. See Figure 7-5.

$$I_{R1} \cong I_{R2} = \frac{15\text{ V}}{86\ \Omega} = 174\text{ mA}$$

$$V_B \cong \left(\frac{18\ \Omega}{86\ \Omega}\right)15\text{ V} = 3.14\text{ V}$$

$V_E = 3.14\text{ V} - 0.7\text{ V} = 2.44\text{ V}$

$$I_E \cong I_C = \frac{2.44\text{ V}}{4.85\ \Omega} = 503\text{ mA}$$

$V_C = 15\text{ V} - (10\ \Omega)(503\text{ mA}) = 9.97\text{ V}$

$V_{CE} = 7.53\text{ V}$

$$r'_e = \frac{25\text{ mV}}{503\text{ mA}} = 0.05\ \Omega$$

The ac resistance affecting the load line is

$R_c + R_e + r'_e = 10\ \Omega$

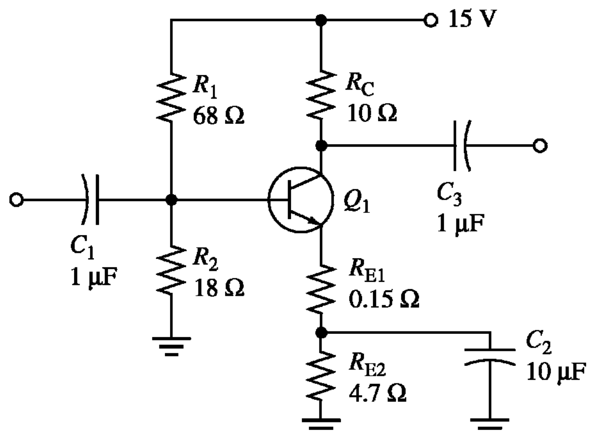

Figure 7-5

$\beta_{ac} = \beta_{DC} \geq 100$

$$I_{c(sat)} = 503\text{ mA} + \frac{7.53\text{ V}}{10.2\ \Omega} = 1.24\text{ A}$$

$V_{ce(cutoff)} = 7.53\text{ V} + (503\text{ mA})(10.2\ \Omega) = 12.7\text{ V}$

The Q-point is closer to cutoff so

$P_{out} = (0.5)(503\text{ mA})^2(10.2\ \Omega) = 1.29\text{ W}$

As loading occurs, the Q-point will still be closer to cutoff. The circuit will have

$P_{out} \geq 1\text{ W}$ for $R_L \geq 37.7\ \Omega$. (39 Ω standard)

40. Preamp quiescent current:

$$I_1 = I_2 = \frac{30\text{ V}}{660\text{ k}\Omega} = 45\ \mu\text{A}$$

$$I_3 = I_4 = I_5 = \frac{15\text{ V} - 0.7\text{ V}}{34\text{ k}\Omega} = 421\ \mu\text{A}$$

$$I_6 = I_7 = \frac{30\text{ V}}{69\text{ k}\Omega} = 435\ \mu\text{A}$$

$V_{B2} = 15\text{ V} - (435\ \mu\text{A})(47\text{ k}\Omega) = -5.45\text{ V}$

$$I_8 = I_9 = I_{10} = \frac{-15\text{ V} - (-5.45\text{ V} - 0.7\text{ V})}{5.13\text{ k}\Omega} = 1.73\text{ mA}$$

$I_{tot} = 45\ \mu\text{A} + 421\ \mu\text{A} + 435\ \mu\text{A} + 1.73\text{ mA} = 2.63\text{ mA}$

Power amp quiescent current:

$I_{11} \cong 0$

$$I_{12} = \frac{15.7\text{ V} - 3(0.7\text{ V})}{1.0\text{ k}\Omega} = \frac{13.6\text{ V}}{1.0\text{ k}\Omega} = 13.6\text{ mA}$$

$$I_{13} = \frac{-15\text{ V} - (-0.7\text{ V})}{220\ \Omega} = \frac{-14.3\text{ V}}{220\ \Omega} = 65\text{ mA}$$

$I_{tot} = 13.6\text{ mA} + 65\text{ mA} = 78.6\text{ mA}$

Signal current to load:

Scope shows ≈ 9.8 V peak output.

$$I_L = \frac{0.707(9.8\text{ V})}{8\ \Omega} = 866\text{ mA}$$

$I_{tot(\text{sys})} = 2.63\text{ mA} + 78.6\text{ mA} + 866\text{ mA} = 947\text{ mA}$

Amp. × hrs = 947 mA × 4 hrs = 3.79 Ah

Multisim Troubleshooting Problems

41. C_{in} open

42. R_{E2} open

43. Q_1 collector-emitter open

44. D_2 shorted

45. Q_2 drain-source open

Chapter 8
Field-Effect Transistors (FETs)

Section 8-1 The JFET

1. (a) A greater V_{GS} **narrows** the depletion region.

(b) The channel resistance **increases** with increased V_{GS}.

2. The gate-to-source voltage of an *n*-channel JFET must be zero or negative in order to maintain the required reverse-bias condition.

3. See Figure 8-1.

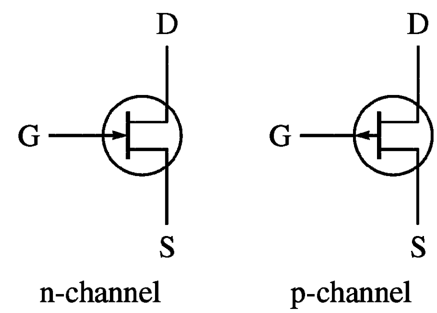

Figure 8-1

4. See Figure 8-2.

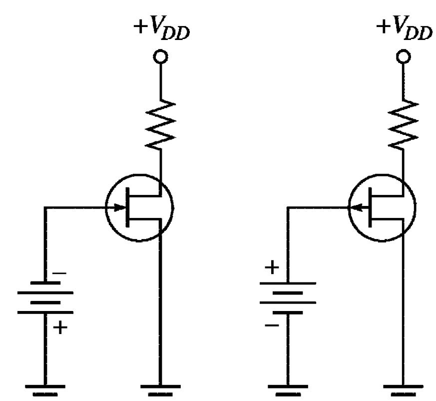

Figure 8-2

Chapter 8

Section 8-2 JFET Characteristics and Parameters

5. $V_{DS} = V_P = \mathbf{5\ V}$ at point where I_D becomes constant.

6. $V_{GS(off)} = -V_P = \mathbf{-6\ V}$

The device is **on**, because $V_{GS} = -2$ V.

7. By definition, $I_D = I_{DSS}$ when $V_{GS} = 0$ V for values of $V_{DS} > V_P$.

Therefore, $I_D = \mathbf{10\ mA}$.

8. Since $V_{GS} > V_{GS(off)}$, the JFET is off and $I_D = \mathbf{0\ A}$.

9. $V_P = -V_{GS(off)} = -(-4\text{ V}) = 4$ V

The voltmeter reads V_{DS}. As V_{DD} is increased, V_{DS} also increases. The point at which I_D reaches a constant value is $V_{DS} = V_P = \mathbf{4\ V}$.

10. $$I_D = I_{DSS}\left(1-\frac{V_{GS}}{V_{GS(off)}}\right)^2$$

$$I_D = 5\text{ mA}\left(1-\frac{0\text{ V}}{-8\text{ V}}\right)^2 = 5\text{ mA}$$

$$I_D = 5\text{ mA}\left(1-\frac{-1\text{ V}}{-8\text{ V}}\right)^2 = 3.83\text{ mA}$$

$$I_D = 5\text{ mA}\left(1-\frac{-2\text{ V}}{-8\text{ V}}\right)^2 = 2.81\text{ mA}$$

$$I_D = 5\text{ mA}\left(1-\frac{-3\text{ V}}{-8\text{ V}}\right)^2 = 1.95\text{ mA}$$

$$I_D = 5\text{ mA}\left(1-\frac{-4\text{ V}}{-8\text{ V}}\right)^2 = 1.25\text{ mA}$$

$$I_D = 5\text{ mA}\left(1-\frac{-5\text{ V}}{-8\text{ V}}\right)^2 = 0.703\text{ mA}$$

$$I_D = 5\text{ mA}\left(1-\frac{-6\text{ V}}{-8\text{ V}}\right)^2 = 0.313\text{ mA}$$

$$I_D = 5\text{ mA}\left(1-\frac{-7\text{ V}}{-8\text{ V}}\right)^2 = 0.078\text{ mA}$$

$$I_D = 5\text{ mA}\left(1-\frac{-8\text{ V}}{-8\text{ V}}\right)^2 = 0\text{ mA}$$

See Figure 8-3.

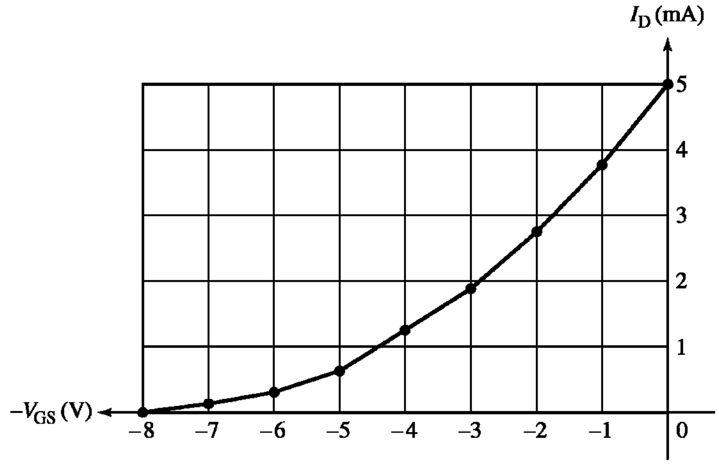

Figure 8-3

11. $$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

$$1 - \frac{V_{GS}}{V_{GS(off)}} = \sqrt{\frac{I_D}{I_{DSS}}}$$

$$\frac{V_{GS}}{V_{GS(off)}} = 1 - \sqrt{\frac{I_D}{I_{DSS}}}$$

$$V_{GS} = V_{GS(off)}\left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right)$$

$$V_{GS} = -8\text{ V}\left(1 - \sqrt{\frac{2.25\text{ mA}}{5\text{ mA}}}\right) = -8\text{ V}(0.329) = \mathbf{-2.63\ V}$$

12. $$g_m = g_{m0}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right) = 3200\ \mu\text{S}\left(1 - \frac{-4\text{V}}{-8\text{V}}\right) = \mathbf{1600\ \mu S}$$

13. $$g_m = g_{m0}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right) = 2000\ \mu\text{S}\left(1 - \frac{-2\text{V}}{-7\text{V}}\right) = \mathbf{1429\ \mu S}$$

$g_{fs} = g_m =$ **1429 μS**

14. $$R_{IN} = \frac{V_{GS}}{I_{GSS}} = \frac{10\text{V}}{5\text{ nA}} = \mathbf{2000\ M\Omega}$$

15. $V_{GS} = 0\text{ V: } I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2 = 8\text{ mA}(1-0)^2 = \mathbf{8\text{ mA}}$

$V_{GS} = -1\text{ V: } I_D = 8\text{ mA}\left(1 - \frac{-1\text{ V}}{-5\text{ V}}\right)^2 = 8\text{ mA}(1-0.2)^2 = 8\text{ mA}(0.8)^2 = \mathbf{5.12\text{ mA}}$

$V_{GS} = -2\text{ V: } I_D = 8\text{ mA}\left(1 - \frac{-2\text{ V}}{-5\text{ V}}\right)^2 = 8\text{ mA}(1-0.4)^2 = 8\text{ mA}(0.6)^2 = \mathbf{2.88\text{ mA}}$

$V_{GS} = -3\text{ V: } I_D = 8\text{ mA}\left(1 - \frac{-3\text{ V}}{-5\text{ V}}\right)^2 = 8\text{ mA}(1-0.6)^2 = 8\text{ mA}(0.4)^2 = \mathbf{1.28\text{ mA}}$

$V_{GS} = -4\text{ V: } I_D = 8\text{ mA}\left(1 - \frac{-4\text{ V}}{-5\text{ V}}\right)^2 = 8\text{ mA}(1-0.8)^2 = 8\text{ mA}(0.2)^2 = \mathbf{0.320\text{ mA}}$

$V_{GS} = -5\text{ V: } I_D = 8\text{ mA}\left(1 - \frac{-5\text{ V}}{-5\text{ V}}\right)^2 = 8\text{ mA}(1-1)^2 = 8\text{ mA}(0)^2 = \mathbf{0\text{ mA}}$

Section 8-3 JFET Biasing

16. See Figure 8-4.

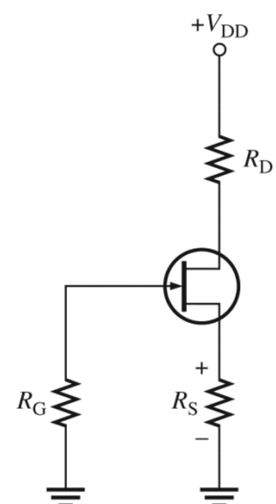

Figure 8-4

17. See Figure 8-5.

(a)

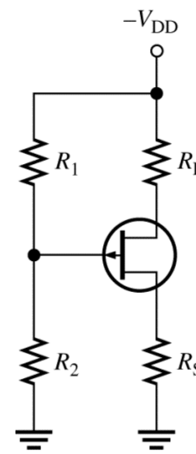

Figure 8-5a

(b)

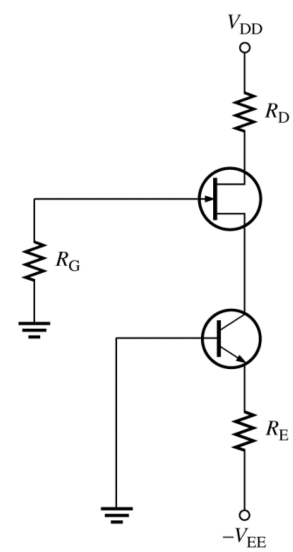

Figure 8-5b

18. $V_{GS} = -I_D R_S = -(12\text{ mA})(100\ \Omega) = -1.2\text{ V}$

19. $R_S = \left|\dfrac{V_{GS}}{I_D}\right| = \left|\dfrac{-4\text{ V}}{5\text{ mA}}\right| = \mathbf{800\ \Omega}$

20. $R_S = \left|\dfrac{V_{GS}}{I_D}\right| = \left|\dfrac{-3\text{ V}}{2.5\text{ mA}}\right| = \mathbf{1.2\ k\Omega}$

Chapter 8

21. (a) $I_D = I_{DSS} =$ **20 mA**

(b) $I_D =$ **0 A**

(c) I_D increases

22. (a) $V_S = (1\text{ mA})(1.0\text{ k}\Omega) = 1\text{ V}$

$V_D = 12\text{ V} - (1\text{ mA})(4.7\text{ k}\Omega) = 7.3\text{ V}$

$V_G = 0\text{ V}$

$V_{GS} = V_G - V_S = 0\text{ V} - 1\text{ V} = \mathbf{-1\text{ V}}$

$V_{DS} = 7.3\text{ V} - 1\text{ V} = \mathbf{6.3\text{ V}}$

(b) $V_S = (5\text{ mA})(100\ \Omega) = 0.5\text{ V}$

$V_D = 9\text{ V} - (5\text{ mA})(470\ \Omega) = 6.65\text{ V}$

$V_G = 0\text{ V}$

$V_{GS} = V_G - V_S = 0\text{ V} - 0.5\text{ V} = \mathbf{-0.5\text{ V}}$

$V_{DS} = 6.65\text{ V} - 0.5\text{ V} = \mathbf{6.15\text{ V}}$

(c) $V_S = (-3\text{ mA})(470\ \Omega) = -1.41\text{ V}$

$V_D = -15\text{ V} - (3\text{ mA})(2.2\text{ k}\Omega) = -8.4\text{ V}$

$V_G = 0\text{ V}$

$V_{GS} = V_G - V_S = 0\text{ V} - (-1.41\text{ V}) = \mathbf{1.41\text{ V}}$

$V_{DS} = -8.4\text{ V} - (-1.41\text{ V}) = \mathbf{-6.99\text{ V}}$

23. From the graph, $V_{GS} \cong -2\text{ V}$ at $I_D = 9.5\text{ mA}$.

$$R_S = \left|\frac{V_{GS}}{I_D}\right| = \left|\frac{-2\text{ V}}{9.5\text{ mA}}\right| = \mathbf{211\ \Omega}$$

24.

$$I_D = \frac{I_{DSS}}{2} = \frac{14\text{ mA}}{2} = \mathbf{7\text{ mA}}$$

$$V_{GS} = \frac{V_{GS(off)}}{3.414} = \frac{-10\text{ V}}{3.414} = \mathbf{-2.93\text{ V}}$$

$$R_S = \left|\frac{V_{GS}}{I_D}\right| = \frac{2.93\text{ V}}{7\text{ mA}} = \mathbf{419\ \Omega}$$

(The nearest standard value is 430 Ω.)

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{24\text{ V} - 12\text{ V}}{7\text{ mA}} = \mathbf{1.7\text{ k}\Omega}$$

(The nearest standard value is 1.8 kΩ.)

Select $R_G = 1.0\ \text{M}\Omega$. See Figure 8-6.

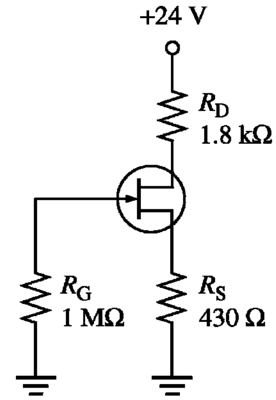

Figure 8-6

25. $R_{\text{IN(total)}} = R_G \parallel R_{\text{IN}}$

$$R_{\text{IN}} = \left|\frac{V_{GS}}{I_{GSS}}\right| = \left|\frac{-10\ \text{V}}{20\ \text{nA}}\right| = 500\ \text{M}\Omega$$

$$R_{\text{IN(total)}} = 10\ \text{M}\Omega \parallel 500\ \text{M}\Omega = \mathbf{9.8\ M\Omega}$$

26. For $I_D = 0$,

$V_{GS} = -I_D R_S = (0)(330\ \Omega) = 0\ \text{V}$

For $I_D = I_{DSS} = 5\ \text{mA}$

$V_{GS} = -I_D R_S = -(5\ \text{mA})(330\ \Omega) = -1.65\ \text{V}$

From the graph in Figure 8-69 in the textbook, the *Q*-point is

$V_{GS} \cong \mathbf{-0.95\ V}$ and $I_D \cong \mathbf{2.9\ mA}$

27. For $I_D = 0$,

$V_{GS} = 0\ \text{V}$

For $I_D = I_{DSS} = 10\ \text{mA}$,

$V_{GS} = -I_D R_S = (10\ \text{mA})(390\ \Omega) = 3.9\ \text{V}$

From the graph in Figure 8-70 in the textbook, the *Q*-point is

$V_{GS} \cong \mathbf{2.1\ V}$ and $I_D \cong \mathbf{5.3\ mA}$

28. Since $V_{R_D} = 9\ \text{V} - 5\ \text{V} = 4\ \text{V}$

$$I_D = \frac{V_{R_D}}{R_D} = \frac{4\ \text{V}}{4.7\ \text{k}\Omega} = 0.85\ \text{mA}$$

$$V_S = I_D R_S = (0.85\ \text{mA})(3.3\ \text{k}\Omega) = 2.81\ \text{V}$$

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$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{2.2\text{ M}\Omega}{12.2\text{ M}\Omega}\right)9\text{ V} = 1.62\text{ V}$$

$$V_{GS} = V_G - V_S = 1.62\text{ V} - 2.81\text{ V} = -1.19\text{ V}$$

Q-point: $I_D = \mathbf{0.85\ mA}$, $V_{GS} = \mathbf{-1.19\ V}$

29. For $I_D = 0$,

$$V_{GS} = V_G = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{2.2\text{ M}\Omega}{5.5\text{ M}\Omega}\right)12\text{ V} = 4.8\text{ V}$$

For $V_{GS} = 0$ V, $V_S = 4.8$ V

$$I_D = \frac{V_S}{R_S} = \frac{|V_G - V_{GS}|}{R_S} = \frac{4.8\text{ V}}{3.3\text{ k}\Omega} = 1.45\text{ mA}$$

The Q-point is taken from the graph in Figure 8-75 in the textbook.

$I_D \cong \mathbf{1.9\ mA}$, $V_{GS} \cong \mathbf{-1.5\ V}$

Section 8-4 The Ohmic Region

30. $$R_{DS} = \frac{V_{DS}}{I_D} = \frac{0.8\text{ V}}{0.20\text{ mA}} = \mathbf{4\ k\Omega}$$

31. $$R_{DS1} = \frac{0.4\text{ V}}{0.15\text{ mA}} = 2.67\text{ k}\Omega$$

$$R_{DS2} = \frac{0.6\text{ V}}{0.45\text{ mA}} = 1.33\text{ k}\Omega$$

$$\Delta R_{DS} = 2.67\text{ k}\Omega - 1.33\text{ k}\Omega = \mathbf{1.34\ k\Omega}$$

32. $$g_m = g_{m0}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right) = 1.5\text{ mS}\left(1 - \frac{-1\text{V}}{-3.5\text{V}}\right)$$

$$= 1.5\text{ mS}(0.714) = \mathbf{1.07\ mS}$$

33. $$r_{ds} = \frac{1}{g_m} = \frac{1}{1.07\text{ mS}} = \mathbf{935\ \Omega}$$

Section 8-5 The MOSFET

34. See Figure 8-7.

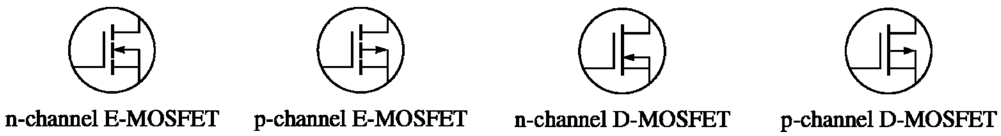

Figure 8-7

35. An *n*-channel D-MOSFET with a positive V_{GS} is operating in the **enhancement mode.**

36. An E-MOSFET has no physical channel or depletion mode. A D-MOSFET has a physical channel and can be operated in either depletion or enhancement modes.

37. MOSFETs have a very high input resistance because the gate is insulated from the channel by an SiO_2 layer.

Section 8-6 MOSFET Characteristics and Parameters

38. $$K = \frac{I_{D(on)}}{\left(V_{GS} - V_{GS(th)}\right)^2} = \frac{10\text{ mA}}{(-12\text{ V} + 3\text{ V})^2} = 0.12\text{ mA/V}^2$$

$$I_D = K\left(V_{GS} - V_{GS(off)}\right)^2 = (0.12\text{ mA/V}^2)(-6\text{ V} + 3\text{ V})^2 = \mathbf{1.08\text{ mA}}$$

39. $$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

$$I_{DSS} = \frac{I_D}{\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2} = \frac{3\text{ mA}}{\left(1 - \frac{-2\text{ V}}{-10\text{ V}}\right)^2} = \mathbf{4.69\text{ mA}}$$

40. (a) *n* channel

(b) $$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2 \qquad I_D = 8\text{ mA}\left(1 - \frac{-5\text{ V}}{-5\text{ V}}\right)^2 = \mathbf{0\text{ mA}}$$

$$I_D = 8\text{ mA}\left(1 - \frac{-4\text{ V}}{-5\text{ V}}\right)^2 = \mathbf{0.32\text{ mA}} \qquad I_D = 8\text{ mA}\left(1 - \frac{-3\text{ V}}{-5\text{ V}}\right)^2 = \mathbf{1.28\text{ mA}}$$

$$I_D = 8\text{ mA}\left(1 - \frac{-2\text{ V}}{-5\text{ V}}\right)^2 = \mathbf{2.88\text{ mA}} \qquad I_D = 8\text{ mA}\left(1 - \frac{-1\text{ V}}{-5\text{ V}}\right)^2 = \mathbf{5.12\text{ mA}}$$

$$I_D = 8\text{ mA}\left(1 - \frac{0\text{ V}}{-5\text{ V}}\right)^2 = \mathbf{8\text{ mA}} \qquad I_D = 8\text{ mA}\left(1 - \frac{1\text{ V}}{-5\text{ V}}\right)^2 = \mathbf{11.5\text{ mA}}$$

$$I_D = 8\text{ mA}\left(1 - \frac{2\text{ V}}{-5\text{ V}}\right)^2 = \mathbf{15.7\text{ mA}} \qquad I_D = 8\text{ mA}\left(1 - \frac{3\text{ V}}{-5\text{ V}}\right)^2 = \mathbf{20.5\text{ mA}}$$

$$I_D = 8\text{ mA}\left(1 - \frac{4\text{ V}}{-5\text{ V}}\right)^2 = \mathbf{25.9\text{ mA}} \qquad I_D = 8\text{ mA}\left(1 - \frac{5\text{ V}}{-5\text{ V}}\right)^2 = \mathbf{32\text{ mA}}$$

(c) See Figure 8-8.

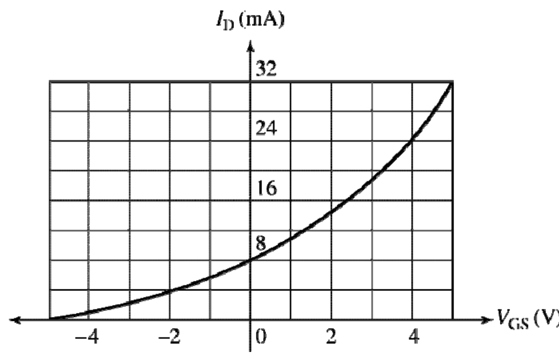

Figure 8-8

Section 8-7 MOSFET Biasing

41. (a) Depletion

(b) Enhancement

(c) Zero bias

(d) Depletion

42. (a) $V_{GS} = \left(\frac{10\text{ M}\Omega}{14.7\text{ M}\Omega}\right)10\text{ V} = \mathbf{6.8\text{ V}}$ This MOSFET is **on**.

(b) $V_{GS} = \left(\frac{1.0\text{ M}\Omega}{11\text{ M}\Omega}\right)(-25\text{ V}) = \mathbf{-2.27\text{ V}}$ This MOSFET is **off**.

43. Since $V_{GS} = 0$ V for each circuit, $I_D = I_{DSS} = 8$ mA.

(a) $V_{DS} = V_{DD} - I_D R_D = 12\text{ V} - (8\text{ mA})(1.0\text{ k}\Omega) = \mathbf{4\text{ V}}$

(b) $V_{DS} = V_{DD} - I_D R_D = 15\text{ V} - (8\text{ mA})(1.2\text{ k}\Omega) = \mathbf{5.4\text{ V}}$

(c) $V_{DS} = V_{DD} - I_D R_D = -9\text{ V} - (-8\text{ mA})(560\ \Omega) = \mathbf{-4.52\text{ V}}$

44. (a) $I_{D(on)} = 3\,mA$ @ 4 V, $V_{GS(th)} = 2$ V

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{4.7\ M\Omega}{14.7\,M\Omega}\right)10\,V = \mathbf{3.2\ V}$$

$$K = \frac{I_{D(on)}}{\left(V_{GS} - V_{GS(th)}\right)^2} = \frac{3\ mA}{(4\ V - 2\ V)^2} = \frac{3\ mA}{(2\,V)^2} = 0.75\ mA/V^2$$

$$I_D = K\left(V_{GS} - V_{GS(th)}\right)^2 = (0.75\ mA/V^2)(3.2\ V - 2\ V)^2 = 1.08\ mA$$

$$V_{DS} = V_{DD} - I_D R_D = 10\,V - (1.08\ mA)(1.0\ k\Omega) = 10\ V - 1.08\ V = \mathbf{8.92\ V}$$

(b) $I_{D(on)} = 2\,mA$ @ 3 V, $V_{GS(th)} = 1.5$ V

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{10\ M\Omega}{20\,M\Omega}\right)5\,V = \mathbf{2.5\ V}$$

$$K = \frac{I_{D(on)}}{\left(V_{GS} - V_{GS(th)}\right)^2} = \frac{2\ mA}{(3\ V - 1.5\ V)^2} = \frac{2\ mA}{(1.5\,V)^2} = 0.89\ mA/V^2$$

$$I_D = K\left(V_{GS} - V_{GS(th)}\right)^2 = (0.89\ mA/V^2)(2.5\ V - 1.5\ V)^2 = 0.89\ mA$$

$$V_{DS} = V_{DD} - I_D R_D = 5\,V - (0.89\ mA)(1.5\ k\Omega) = 5\ V - 1.34\ V = \mathbf{3.66\ V}$$

45. (a) $V_{DS} = V_{GS} = \mathbf{5\,V}$

$$I_D = \frac{V_{DD} - V_{DS}}{R_D} = \frac{12\ V - 5\ V}{2.2\ k\Omega} = \mathbf{3.18\,mA}$$

(b) $V_{DS} = V_{GS} = \mathbf{3.2\ V}$

$$I_D = \frac{V_{DD} - V_{DS}}{R_D} = \frac{8\ V - 3.2\ V}{4.7\ k\Omega} = \mathbf{1.02\,mA}$$

46. $V_{DS} = V_{DD} - I_D R_D = 15\,V - (1\ mA)(8.2\ k\Omega) = 6.8\ V$

$V_{GS} = V_{DS} - I_G R_G = 6.8\,V - (50\ pA)(22\ M\Omega) = \mathbf{6.799\ V}$

Section 8-8 The IGBT

47. The input resistance of an IGBT is very high because of the insulated gate structure.

48. With excessive collector current, the parasitic transistor turns on and the IGBT acts as a thyristor.

Section 8-9 Troubleshooting

49. When I_D goes to zero, the possible faults are:
R_D or R_S open, JFET drain-to-source open, no supply voltage, or ground connection open.

50. If I_D goes to 16 mA, the possible faults are:
The JFET is shorted from drain-to-source or V_{DD} has increased.

51. If V_{DD} is changed to –20 V, I_D will change very little or none because the device is operating in the constant-current region of the characteristic curve.

52. The device is off. The gate bias voltage must be less than $V_{GS(th)}$. The gate could be shorted or partially shorted to ground.

53. The device is saturated, so there is very little voltage from drain-to-source. This indicates that V_{GS} is too high. The 1.0 MΩ bias resistor is probably **open**.

Device Application Problems

54. (a) –500 mV

(b) –200 mV

(c) 0 mV

(d) 400 mV

55. At $V_{G2S} = 6\text{ V},\ \ I_D \cong 10\text{ mA}$

At $V_{G2S} = 1\text{ V},\ \ I_D \cong 5\text{ mA}$

56. $V_{G1S} = V_{sensor} = -400\text{ mV}$

$V_{OUT} = 9.048\text{ V}$

$$I_D = \frac{V_{DD} - V_{OUT}}{R_3 + R_4} = \frac{12\text{ V} - 9.048\text{ V}}{1120\ \Omega} = \mathbf{2.64\ mA}$$

$V_{G1S} = V_{sensor} = -300\text{ mV}$

$V_{OUT} = 7.574\text{ V}$

$$I_D = \frac{12\text{ V} - 7.574\text{ V}}{1120\ \Omega} = \mathbf{3.95\ mA}$$

$V_{G1S} = V_{sensor} = -200\text{ mV}$

$V_{OUT} = 5.930\text{ V}$

$$I_D = \frac{12\text{ V} - 5.930\text{ V}}{1120\ \Omega} = \mathbf{5.42\ mA}$$

$V_{G1S} = V_{sensor} = -100\text{ mV}$

$V_{OUT} = 4.890$ V

$$I_D = \frac{12\text{ V} - 4.890\text{ V}}{1120\ \Omega} = \mathbf{6.35\ mA}$$

$V_{G1S} = V_{sensor} = 0$ mV

$V_{OUT} = 4.197$ V

$$I_D = \frac{12\text{ V} - 4.197\text{ V}}{1120\ \Omega} = \mathbf{6.97\ mA}$$

$V_{G1S} = V_{sensor} = 100$ mV

$V_{OUT} = 3.562$ V

$$I_D = \frac{12\text{ V} - 3.562\text{ V}}{1120\ \Omega} = \mathbf{7.35\ mA}$$

$V_{G1S} = V_{sensor} = 200$ mV

$V_{OUT} = 2.960$ V

$$I_D = \frac{12\text{ V} - 2.960\text{ V}}{1120\ \Omega} = \mathbf{8.07\ mA}$$

$V_{G1S} = V_{sensor} = 300$ mV

$V_{OUT} = 2.382$ V

$$I_D = \frac{12\text{ V} - 2.382\text{ V}}{1120\ \Omega} = \mathbf{8.59\ mA}$$

See Figure 8-9.

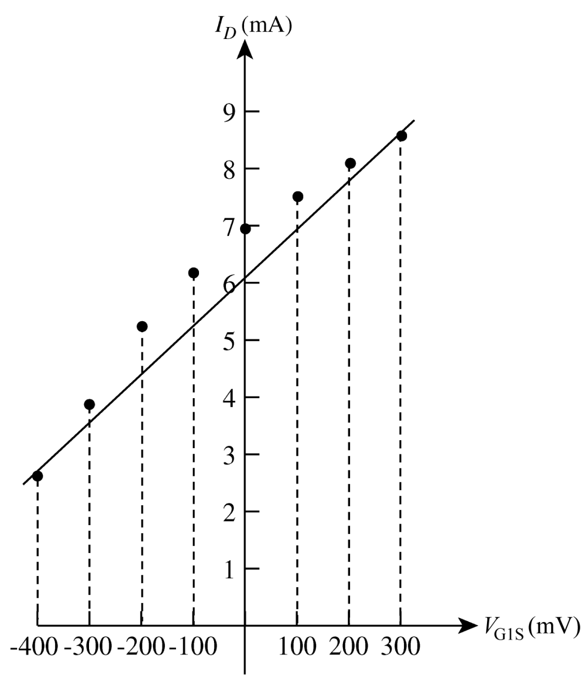

Figure 8-9

57. $V_{G2S} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{50\text{ k}\Omega}{150\text{ k}\Omega}\right)12\text{ V} = 4\text{ V}$

From the graph in Figure 8-82 in the textbook for $V_{G1S} = 0$ and $V_{G2S} = 4$ V:

$I_D \cong 8\text{ mA}$

$V_{OUT} = 12\text{ V} - (8\text{ mA})(1120\ \Omega) = \mathbf{3.04\ V}$

Datasheet Problems

58. The 2N5457 is an ***n*-channel JFET**.

59. From the datasheet in textbook Figure 8-14:

(a) For a 2N5457, $V_{GS(off)} = \mathbf{-0.5\ V}$ minimum

(b) For a 2N5457, $V_{DS(max)} = \mathbf{25\ V}$

(c) For a 2N5458 @ 25°C, $P_{D(max)} = \mathbf{310\ mW}$

(d) For a 2N5459, $V_{GS(rev)} = \mathbf{-25\ V}$ maximum

60. $P_{D(max)} = 310\text{ mW} - (2.82\text{ mW/°C})(65°\text{C} - 25°\text{C}) = 310\text{ mW} - 113\text{ mW} = \mathbf{197\ mW}$

61. $g_{m0(min)} = g_{fs} = \mathbf{2000\ \mu S}$

62. Typical $I_D = I_{DSS} = \mathbf{9\ mA}$

63. From the datasheet graph in textbook Figure 8-80:

$I_D \cong 1.4\text{ mA}$ at $V_{GS} = 0$

64. For a 2N3796 with $V_{GS} = 6\text{ V}$, $I_D = \mathbf{15\ mA}$

65. From the datasheet graph in textbook Figure 8-83:

At $V_{GS} = +3\text{ V}$, $I_D = \mathbf{13\ mA}$

At $V_{GS} = -2\text{ V}$, $I_D = 0.4\ \mathbf{mA}$

66. $y_{fs} = 1500\ \mu\text{S}$ at f = 1 kHz and at f = 1 MHz for both the 2N3796 and 2N3797. There is **no change** in g_{fs} over the frequency range.

67. For a 2N3796, $V_{GS(off)} = \mathbf{-3.0\ V}$ typical

Advanced Problems

68. For the circuit of textbook Figure 8-84:

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2 \text{ where } V_{GS} = I_D R_S$$

From the 2N5457 datasheet:

$I_{DSS(min)}$ = 1.0 mA and $V_{GS(off)}$ = –0.5 V minimum

$I_D = 66.3\ \mu\text{A}$

$V_{GS} = -(66.3\ \mu\text{A})(5.6\ \text{k}\Omega) = \mathbf{-0.371\ V}$

$V_{DS} = 12\ \text{V} - (66.3\ \mu\text{A})(10\ \text{k}\Omega + 5.6\text{k}\Omega) = \mathbf{11.0\ V}$

69. For the circuit of textbook Figure 8-85:

$$V_C = \left(\frac{3.3\ \text{k}\Omega}{13.3\ \text{k}\Omega}\right)9\,\text{V} = (0.248)(9\,\text{V}) = 2.23\,\text{V}$$

From the equation,

$$I_D = I_{DSS}\left(\frac{V_{GS}}{1 - V_{GS(off)}}\right)^2 \text{ where } V_{GS} = V_G - I_D R_S$$

I_D is maximum for $I_{DSS(max)}$ and $V_{GS(off)}$ max, so that

I_{DSS} = 16 mA and $V_{GS(off)}$ = –8.0 V

I_D = **3.58 mA**

$V_{GS} = 2.23\ \text{V} - (3.58\ \text{mA})(1.8\ \text{k}\Omega) = 2.23\ \text{V} - 6.45\ \text{V} = \mathbf{-4.21\ V}$

70. From the 2N5457 datasheet:

$I_{DSS(min)} = 1.0\ \text{mA}$ and $V_{GS(off)} = -0.5$ minimum

$I_{D(min)} = \mathbf{66.3\ \mu A}$

$V_{DS(max)} = 12\ \text{V} - (66.3\ \mu\text{A})(15.6\ \text{k}\Omega) = \mathbf{11.0\ V}$

and

$I_{DSS(max)} = 5.0\ \text{mA}$ and $V_{GS(off)} = -6.0$ maximum

$I_{D(max)} = \mathbf{677\ \mu A}$

$V_{DS(min)} = 12\ \text{V} - (677\ \mu\text{A})(15.6\ \text{k}\Omega) = \mathbf{1.4\ V}$

71. $V_{\text{pH}} = +300\,\text{mV}$

$I_{\text{D}} = (2.9\text{ mA})(1 + 0.3\text{ V}/5.0\text{ V})^2 = (2.9\text{ mA})(1.06)^2 = 3.26\text{ mA}$

$V_{\text{DS}} = 15\text{ V} - (3.26\text{ mA})(2.76\text{ k}\Omega) = 15\text{ V} - 8.99\text{ V} = \mathbf{+6.01\text{ V}}$

72. $$1\text{ mA} = I_{\text{DSS}}\left(1 - \frac{(1\text{ mA})R_{\text{S}}}{V_{\text{GS(off)}}}\right)^2$$

$$1\text{ mA} = 2.9\text{ mA}\left(1 - \frac{(1\text{ mA})R_{\text{S}}}{-0.5\text{ V}}\right)^2$$

$$0.345 = \left(1 - \frac{(1\text{ mA})R_{\text{S}}}{-0.5\text{ V}}\right)^2$$

$$0.587 = 1 - \frac{(1\text{ mA})R_{\text{S}}}{-0.5\text{ V}}$$

$$0.413 = \frac{(1\text{ mA})R_{\text{S}}}{-0.5\text{ V}}$$

$R_{\text{S}} = 2.06\text{ k}\Omega$

Use R_{S} = **2.2 kΩ**.

Then $I_{\text{D}} = 963\ \mu\text{A}$

$V_{\text{GS}} = V_{\text{S}} = (963\,\mu\text{A})(2.2\,\text{k}\Omega) = 2.19\text{ V}$

So, $V_{\text{D}} = 2.19\text{ V} + 4.5\text{ V} = 6.62\text{ V}$

$$R_{\text{D}} = \frac{9\text{ V} - 6.62\text{ V}}{963\,\mu\text{A}} = 2.47\text{ k}\Omega$$

Use R_{D} = **2.4 kΩ**.

So, $V_{\text{DS}} = 9\text{ V} - (963\,\mu\text{A})(4.6\,\text{k}\Omega) = 4.57\,\text{V}$

73. Let $I_{\text{D}} = 20$ mA.

$$R_{\text{D}} = \frac{4\text{ V}}{20\text{ mA}} = \mathbf{200\,\Omega}$$

Let $V_{\text{S}} = 2$ V.

$$R_{\text{S}} = \frac{2\text{ V}}{20\text{ mA}} = \mathbf{100\,\Omega}$$

$$K = \frac{I_{\text{D(on)}}}{(V_{\text{GS(on)}} - V_{\text{GS(th)}})^2} = \frac{500\text{ mA}}{(10\text{ V} - 1\text{V})} = 6.17\text{ mA/V}^2$$

Let $I_{\text{D}} = 20$ mA.

$V_{GS} - 1\text{ V} = 1.8\text{ V}$

$V_{GS} = 2.8\text{ V}$

$V_G = V_S + 2.8\text{ V} = 4.8\text{ V}$

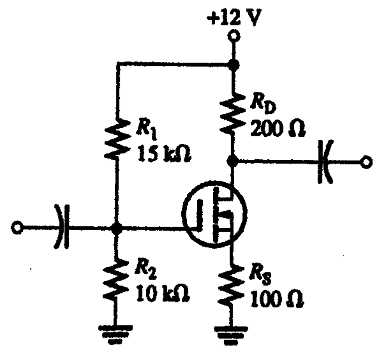

Figure 8-8

For the voltage divider:

$$\frac{R_1}{R_2} = \frac{7.2\text{ V}}{4.8\text{ V}} = 1.5$$

Let R_2 = **10 kΩ**.

R_1 = (1.5)(10 kΩ) = **15 kΩ**

See Figure 8-10.

Multisim Troubleshooting Problems

74. R_S shorted

75. R_D shorted

76. R_G shorted

77. R_1 open

78. Drain-source open

79. R_D open

80. R_2 shorted

81. Drain-source shorted

82. R_1 shorted

Chapter 9
FET Amplifiers and Switching Circuits

Section 9-1 The Common-Source Amplifier

1. Two general approaches for analyzing a JFET circuit are dc analysis and ac analysis.

2. $A_v = g_m R_d = (5\text{ mS})(2.2\text{ k}\Omega) = 11$

3. (a) $I_d = g_m V_{gs} = (6000\ \mu\text{S})(10\text{ mV}) = \mathbf{60\ \mu A}$

(b) $I_d = g_m V_{gs} = (6000\ \mu\text{S})(150\text{ mV}) = \mathbf{900\mu A}$

(c) $I_d = g_m V_{gs} = (6000\ \mu\text{S})(0.6\text{ V}) = \mathbf{3.6\ mA}$

(d) $I_d = g_m V_{gs} = (6000\ \mu\text{S})(1\text{ V}) = \mathbf{6\ mA}$

4. $A_v = g_m R_d$

$$R_d = \frac{A_v}{g_m} = \frac{20}{3500\ \mu\text{S}} = \mathbf{5.71\ k\Omega}$$

5. $$A_v = \left(\frac{R_\text{D} r'_{ds}}{R_\text{D} + r'_{ds}}\right) g_m = \left(\frac{(4.7\text{ k}\Omega)(12\text{ k}\Omega)}{16.7\text{ k}\Omega}\right) 4.2\text{ mS} = \mathbf{14.2}$$

6. $R_d = R_D \parallel r'_{ds} = 4.7\text{ k}\Omega \parallel 12\text{ k}\Omega = 3.38\text{ k}\Omega$

$$A_v = \frac{g_m R_d}{1 + g_m R_s} = \frac{(4.2\text{ mS})(3.38\text{ k}\Omega)}{1 + (4.2\text{ mS})(1.0\text{ k}\Omega)} = \mathbf{2.73}$$

7. (a) *N*-channel D-MOSFET with zero-bias.

$V_\text{GS} = \mathbf{0\ V}$.

(b) *P*-channel JFET with self-bias.

$V_\text{GS} = -I_\text{D} R_\text{S} = (-3\text{ mA})(330\ \Omega) = \mathbf{-0.99\ V}$

(c) *N*-channel E-MOSFET with voltage-divider bias.

$$V_\text{GS} = \left(\frac{R_2}{R_1 + R_2}\right) V_\text{DD} = \left(\frac{4.7\text{ k}\Omega}{14.7\text{ k}\Omega}\right) 12\text{ V} = \mathbf{3.84\ V}$$

8. (a) $V_{\text{G}} = \mathbf{0\ V}, \quad V_{\text{S}} = \mathbf{0\ V}$

$V_{\text{D}} = V_{\text{DD}} - I_{\text{D}}R_{\text{D}} = 15\text{ V} - (8\text{ mA})(1.0\text{ k}\Omega) = \mathbf{7\ V}$

(b) $V_{\text{G}} = \mathbf{0\ V}$

$V_{\text{S}} = -I_{\text{D}}R_{\text{D}} = -(3\text{ mA})(330\ \Omega) = \mathbf{-0.99\ V}$

$V_{\text{D}} = -V_{\text{DD}} + I_{\text{D}}R_{\text{D}} = -10\text{ V} + (3\text{ mA})(1.5\text{ k}\Omega) = \mathbf{-5.5\ V}$

(c) $V_{\text{G}} = \left(\dfrac{R_2}{R_1 + R_2}\right)V_{\text{DD}} = \left(\dfrac{4.7\text{ k}\Omega}{14.7\text{ k}\Omega}\right)12\text{ V} = \mathbf{3.84\ V}$

$V_{\text{S}} = \mathbf{0\ V}$

$V_{\text{D}} = V_{\text{DD}} - I_{\text{D}}R_{\text{D}} = 12\text{ V} - (6\text{ mA})(1.0\text{ k}\Omega) = \mathbf{6\ V}$

9. (a) *n*-channel D-MOSFET

(b) *n*-channel JFET

(c) *p*-channel E-MOSFET

10. From the curve in Figure 9-16(a) in the textbook:

$I_{d(pp)} \cong 3.9\text{ mA} - 1.3\text{ mA} = \mathbf{2.6\ mA}$

11. From the curve in Figure 9-16(b) in the textbook:

$I_{d(pp)} \cong 6\text{ mA} - 2\text{ mA} = \mathbf{4\ mA}$

From the curve in Figure 9-16(c) in the textbook:

$I_{d(pp)} \cong 4.5\text{ mA} - 1.3\text{ mA} = 3.2\ \mathbf{mA}$

12. $V_{\text{D}} = V_{\text{DD}} - I_{\text{D}}R_{\text{D}} = 12\text{ V} - (2.83\text{ mA})(1.5\text{ k}\Omega) = \mathbf{7.76\ V}$

$V_{\text{S}} = I_{\text{D}}R_{\text{S}} = (2.83\text{ mA})(1.0\text{ k}\Omega) = \mathbf{2.83\ V}$

$V_{\text{DS}} = V_{\text{D}} - V_{\text{S}} = 7.76\text{ V} - 2.83\text{ V} = \mathbf{4.93\ V}$

$V_{\text{GS}} = V_{\text{G}} - V_{\text{S}} = 0\text{ V} - 2.83\text{ V} = \mathbf{-2.83\ V}$

13. $A_v = g_m R_d = g_m\left(R_{\text{D}} \parallel R_{\text{L}}\right) = 5000\ \mu\text{S}\left(1.5\text{ k}\Omega \parallel 10\text{ k}\Omega\right) = 6.52$

$V_{pp(out)} = (2.828)(50\text{ mV})(6.52) = \mathbf{920\ mV}$

14. $A_v = g_m R_d$

$R_d = 1.5\text{ k}\Omega \parallel 1.5\text{ k}\Omega = 750\ \Omega$

$A_v = (5000\ \mu\text{S})(750\ \Omega) = 3.75$

$A_{out} = A_v V_{in} = (3.75)(50\text{ mV}) = \mathbf{188\ mV\ rms}$

15. (a) $A_v = g_m R_d = g_m\left(R_D \parallel R_L\right) = 3.8\text{ mS}\left(1.2\text{ k}\Omega \parallel 22\text{ k}\Omega\right) = 3.8\text{ mS}(1138\ \Omega) = \mathbf{4.32}$

(b) $A_v = g_m R_d = g_m\left(R_D \parallel R_L\right) = 5.5\text{ mS}\left(2.2\text{ k}\Omega \parallel 10\text{ k}\Omega\right) = 5.5\text{ mS}(1.8\ \Omega) = \mathbf{9.92}$

16. See Figure 9-1.

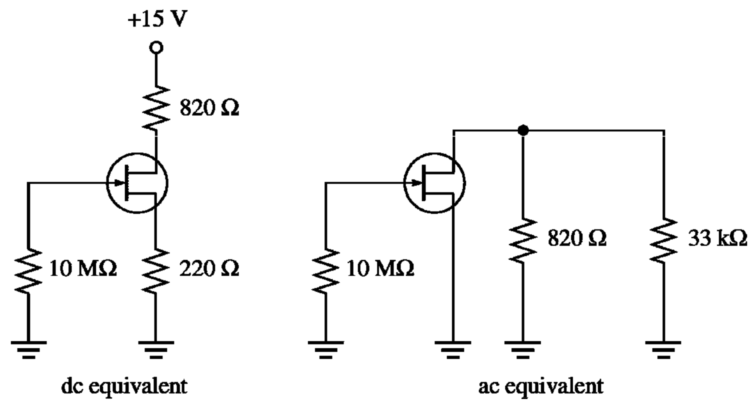

Figure 9-1

17. $$I_D = \frac{I_{DSS}}{2} = \frac{15\text{ mA}}{2} = \mathbf{7.5\ mA}$$

18. $$V_{GS} = (7.5\text{ mA})(220\ \Omega) = 1.65\text{ V}$$

$$g_{m0} = \frac{2I_{DSS}}{\left|V_{GS(off)}\right|} = \frac{2(15\text{ mA})}{4\text{ V}} = 7.5\text{ mS}$$

$$g_m = (7.5\text{ mS})(1 - 1.65\text{ V}/4\text{ V}) = 4.41\text{ mS}$$

$$A_v = \frac{g_m R_d}{1 + g_m R_S} = \frac{(4.41\text{ mS})(820\ \Omega \parallel 3.3\text{ k}\Omega)}{1 + (4.41\text{ mS})(220\ \Omega)} = \frac{(4.41\text{ mS})(657\ \Omega)}{1 + 0.97} = \mathbf{1.47}$$

19. $$A_v = g_m R_d = (4.41\text{ mS})(820\ \Omega \parallel 3.3\text{ k}\Omega \parallel 4.7\text{ k}\Omega) = (4.41\text{ mS})(576\ \Omega) = \mathbf{2.54}$$

20. $$I_D = \frac{I_{DSS}}{2} = \frac{9\text{ mA}}{2} = \mathbf{4.5\ mA}$$

$$V_{GS} = -I_D R_S = -(4.5\text{ mA})(330\ \Omega) = \mathbf{-1.49\ V}$$

$$V_{DS} = V_{DD} - I_D(R_D + R_S) = 9\text{ V} - (4.5\text{ mA})(1.33\text{ k}\Omega) = \mathbf{3\ V}$$

21. $$A_v = g_m R_d = g_m\left(R_D \parallel R_L\right) = 3700\ \mu\text{S}\left(1.0\text{ k}\Omega \parallel 10\text{ k}\Omega\right) = 3700\ \mu\text{S}(909\ \Omega) = 3.36$$

$$V_{out} = A_v V_{in} = (3.36)(10\text{ mV}) = \mathbf{33.6\ mV\ rms}$$

22. $$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{6.8\text{ k}\Omega}{24.8\text{ k}\Omega}\right)20\text{ V} = \mathbf{5.48\text{ V}}$$

$$K = \frac{I_{D(on)}}{(V_{GS} - V_{GS(th)})^2} = \frac{18\text{ mA}}{(10\text{ V} - 2.5\text{ V})^2} = 0.32\text{ mA/V}^2$$

$$I_D = K(V_{GS} - V_{GS(th)})^2 = 0.32\text{ mA/V}^2(5.48\text{ V} - 2.5\text{ V})^2 = \mathbf{2.84\text{ mA}}$$

$$V_{DS} = V_{DD} - I_D R_D = 20\text{ V} - (2.84\text{ mA})(1.0\text{ k}\Omega) = \mathbf{17.2\text{ V}}$$

23. $$R_{IN} = \left|\frac{V_{GS}}{I_{GSS}}\right| = \left|\frac{-15\text{ V}}{25\text{ nA}}\right| = 600\text{ M}\Omega$$

$$R_{in} = 10\text{ M}\Omega \parallel 600\text{ M}\Omega = \mathbf{9.84\text{ M}\Omega}$$

24. $$A_V = g_m R_d = 48\text{ mS}\,(1.0\text{ k}\Omega \parallel 10\text{ M}\Omega) \cong 4.8$$

$$V_{out} = A_v V_{in} = 4.8(10\text{ mV}) = \mathbf{48\text{ mV rms}}$$

$$I_D = I_{DSS} = 15\text{ mA}$$

$$V_D = 24\text{ V} - (15\text{ mA})(1.0\text{ k}\Omega) = \mathbf{9\text{ V}}$$

See Figure 9-2.

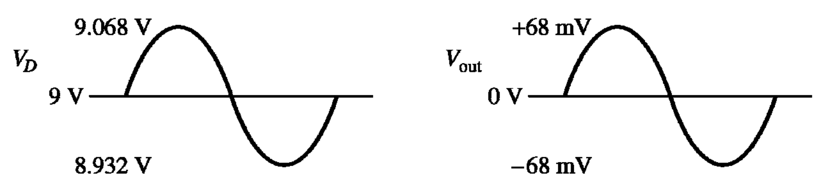

Figure 9-2

25. $$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{47\text{ k}\Omega}{94\text{ k}\Omega}\right)18\text{ V} = \mathbf{9\text{ V}}$$

$$K = \frac{I_{D(on)}}{(V_{GS} - V_{GS(th)})^2} = \frac{8\text{ mA}}{(12\text{ V} - 4\text{ V})^2} = 0.125\text{ mA/V}^2$$

$$I_{D(on)} = K(V_{GS} - V_{GS(th)})^2 = 0.125\text{ mA/V}^2(9\text{ V} - 4\text{ V})^2 = \mathbf{3.13\text{ mA}}$$

$$V_{DS} = V_{DD} - I_D R_D = 18\text{ V} - (3.125\text{ mA})(1.5\text{ k}\Omega) = \mathbf{13.3\text{ V}}$$

$$A_v = g_m R_D = 4500\ \mu S(1.5\text{ k}\Omega) = 6.75$$

$$V_{ds} = A_v V_{in} = 6.75(100\text{ mV}) = \mathbf{675\text{ mV rms}}$$

Chapter 9

Section 9-2 The Common-Drain Amplifier

26. $R_s = 1.2\ \text{k}\Omega \parallel 1\ \text{k}\Omega \cong 545\ \Omega$

$$A_v = \frac{g_m R_s}{1 + g_m R_s} = \frac{(5500\ \mu\text{S})(545\ \Omega)}{1 + (5500\ \mu\text{S})(545\ \Omega)} = \mathbf{0.750}$$

$$R_{\text{IN}} = \left|\frac{V_{\text{GS}}}{I_{\text{GSS}}}\right| = \left|\frac{-15\ \text{V}}{50\ \text{pA}}\right| = 3 \times 10^{11}\ \Omega$$

$$R_{in} = 10\ \text{M}\Omega \parallel 3 \times 10^{11}\ \Omega \cong \mathbf{10\ M\Omega}$$

27. $R_s = 1.2\ \text{k}\Omega \parallel 1\ \text{k}\Omega \cong 545\ \Omega$

$$A_v = \frac{g_m R}{1 + g_m R_s} = \frac{(3000\ \mu\text{S})(545\ \Omega)}{1 + (300\ \mu\text{S})(545\ \Omega)} = \mathbf{0.620}$$

$$R_{\text{IN}} = \left|\frac{V_{\text{GS}}}{I_{\text{GSS}}}\right| = \left|\frac{-15\ \text{V}}{50\ \text{pA}}\right| = 3 \times 10^{11}\ \Omega$$

$$R_{in} = 10\ \text{M}\Omega \parallel 3 \times 10^{11}\ \Omega \cong \mathbf{10\ M\Omega}$$

28. (a) $R_s = 4.7\ \text{k}\Omega \parallel 47\ \text{k}\Omega = 4.27\ \text{k}\Omega$

$$A_v = \frac{g_m R_s}{1 + g_m R_s} = \frac{(3000\ \mu\text{S})(4.27\ \text{k}\Omega)}{1 + (3000\ \mu\text{S})(4.27\ \text{k}\Omega)} = \mathbf{0.928}$$

(b) $R_s = 1.0\ \text{k}\Omega \parallel 100\ \Omega = 90.9\ \Omega$

$$A_v = \frac{g_m R_s}{1 + g_m R_s} = \frac{(4300\ \mu\text{S})(90.9\ \Omega)}{1 + (4300\ \mu\text{S})(90.9\ \Omega)} = \mathbf{0.281}$$

29. (a) $R_s = 4.7\ \text{k}\Omega \parallel 10\ \text{k}\Omega = 3.2\ \text{k}\Omega$

$$A_v = \frac{g_m R_s}{1 + g_m R_s} = \frac{(3000\ \mu\text{S})(3.2\ \text{k}\Omega)}{1 + (3000\ \mu\text{S})(3.2\ \text{k}\Omega)} = \mathbf{0.906}$$

(b) $R_s = 100\ \Omega \parallel 10\ \text{k}\Omega = 99\ \Omega$

$$A_v = \frac{g_m R_s}{1 + g_m R_s} = \frac{(4300\ \mu\text{S})(99\ \Omega)}{1 + (4300\ \mu\text{S})(99\ \Omega)} = \mathbf{0.299}$$

30. The gain will increase for high-resistance sources due to decreased loading.

31. $R_{in} = R_{\text{IN(gate)}} \parallel (R_3 + R_1 \parallel R_2)$

Section 9-3 The Common-Gate Amplifier

32. $A_v = g_m R_d = 4000\ \mu\text{S}(1.5\ \text{k}\Omega) = \mathbf{6.0}$

33. $R_{in(source)} = \dfrac{1}{g_m} = \dfrac{1}{4000\ \mu\text{S}} = \mathbf{250\ \Omega}$

34. $A_v = g_m R_d = 3500\ \mu\text{S}(10\ \text{k}\Omega) = \mathbf{35}$

$$R_{in} = R_\text{S} \left\| \left(\frac{1}{g_m}\right) = 2.2\ \text{k}\Omega \right\| \left(\frac{1}{3500\ \mu\text{S}}\right) = \mathbf{253\ \Omega}$$

35. $X_L = 2\pi f L = 2\pi(100\ \text{MHz})(1.5\ \text{mH}) = 943\ \text{k}\Omega$

$$A_v = g_{m(\text{CG})} X_L = (2800\ \mu\text{S})(943\ \text{k}\Omega) = \mathbf{2640}$$

$$R_{in} = R_3 \left\| \left(\frac{\text{V}_\text{GS}}{I_\text{GSS}}\right) = 15\ \text{M}\Omega \right\| \left(\frac{15\ \text{V}}{2\ \text{nA}}\right)$$

$$= 15\ \text{M}\Omega \parallel 500\ \text{M}\Omega = \mathbf{14.6\ M\Omega}$$

Section 9-4 The Class D Amplifier

36. $A_v = \dfrac{2(9\ \text{V})}{5\ \text{mV}} = \dfrac{18\ \text{V}}{5\ \text{mV}} = 3600$

37. $P_{out} = (12\ \text{V})(0.35\ \text{A}) = 4.2\ \text{W}$

$$P_{int} = (0.25\ \text{V})(0.35\ \text{A}) + 140\ \text{mW}$$

$$= 87.5\ \text{mW} + 140\ \text{mW} = 227.5\ \text{mW}$$

$$\eta = \frac{P_{out}}{P_{out} + P_{int}} = \frac{4.2\ \text{W}}{4.2\ \text{W} + 227.5\ \text{mW}} = \mathbf{0.95}$$

Section 9-5 MOSFET Analog Switching

38. $V_\text{G} - V_{p(out)} = V_{\text{GS(Th)}}$

$$V_{p(out)} = V_\text{G} - V_{\text{GS(Th)}} = 8\ \text{V} - 4\ \text{V} = 4\ \text{V}$$

$$V_{pp(in)} = 2\,V_{p(out)} = 2 \times 4\ \text{V} = \mathbf{8\ V}$$

39. $f_{min} = 2 \times 15\ \text{kHz} = \mathbf{30\ kHz}$

40. $R = \dfrac{1}{fC}$

$$f = \frac{1}{RC} = \frac{1}{(10\ \text{k}\Omega)(10\ \text{pF})} = \mathbf{10\ MHz}$$

41. $R = \dfrac{1}{fC} = \dfrac{1}{(25\text{ kHz})(0.001\ \mu\text{F})} = \mathbf{40\ k\Omega}$

Section 9-6 MOSFET Digital Switching

42. $V_{out} = +5\text{ V}$ when $V_{in} = 0$

$V_{out} = 0\text{ V}$ when $V_{in} = +5\text{ V}$

43. (a) $V_{out} = 3.3\text{ V}$ (b) $V_{out} = 3.3\text{ V}$

(c) $V_{out} = 3.3\text{ V}$ (d) $V_{out} = 0\text{ V}$

44. (a) $V_{out} = 3.3\text{ V}$ (b) $V_{out} = 0\text{ V}$

(c) $V_{out} = 0\text{ V}$ (d) $V_{out} = 0\text{ V}$

45. The MOSFET has lower on-state resistance and can turn off faster.

Section 9-7 Troubleshooting

46. (a) $V_{\text{D1}} = V_{\text{DD}}$; No signal at Q_1 drain; No output signal

(b) $V_{\text{D1}} \cong 0\text{ V}$ (floating); No signal at Q_1 drain; No output signal

(c) $V_{\text{GS1}} = 0\text{ V}$; $V_{\text{S}} = 0\text{ V}$; V_{D1} less than normal; Clipped output signal

(d) Correct signal at Q_1 drain; No signal at Q_2 gate; No output signal

(e) $V_{\text{D2}} = V_{\text{DD}}$; Correct signal at Q_2 gate; No Q_2 drain signal or output signal

47. (a) $V_{out} = 0\text{ V}$ if C_1 is open.

(b) $A_{v1} = g_m R_d = 5000\ \mu\text{S}(1.5\text{ k}\Omega) = 7.5$

$$A_{v2} = \frac{g_m R_d}{1 + g_m R_s} = \frac{7.5}{1 + (5000\ \mu S)(470\ \Omega)} = 2.24$$

$A_v = A_{v1}A_{v2} = (7.5)(2.24) = 16.8$

$V_{out} = A_v V_{in} = (16.8)(10\text{ mV}) = 168\text{ mV}$

(c) V_{GS} for Q_2 is 0 V, so $I_{\text{D}} = I_{\text{DSS}}$. The output is clipped.

(d) No V_{out} because there is no signal at the Q_2 gate.

Datasheet Problems

48. The 2N3796 FET is an ***n*-channel D-MOSFET**.

49. (a) For a 2N3796, the typical $V_{\text{GS(off)}}$ $\mathbf{= -3.0\ V}$

(b) For a 2N3797, $V_{\text{DS(max)}}$ $\mathbf{= 20\ V}$

(c) At $T_{\text{A}} = 25°\text{C}$, $P_{\text{D(max)}}$ $\mathbf{= 200\ mW}$

(d) For a 2N3797, $V_{\text{GS(max)}}$ $\mathbf{= \pm 10\ V}$

50. $P_{\text{D}} = 200\text{ mW} - (1.14\text{ mW/ °C})(55°\text{C} - 25°\text{C}) = \mathbf{166\ mW}$

51. For a 2N3796 with $f = 1\text{ kHz}$, g_{m0} $\mathbf{= 900\ \mu S}$ minimum

52. At $V_{\text{GS}} = 3.5\text{ V}$ and $V_{\text{DS}} = 10\text{ V}$,

$I_{\text{D(min)}}$ $\mathbf{= 9.0\ mA}$, $I_{\text{D(typ)}}$ $\mathbf{= 14\ mA}$, $I_{\text{D(max)}}$ $\mathbf{= 18\ mA}$

53. For a zero-biased 2N3796, $I_{\text{D(typ)}}$ $\mathbf{= 1.5\ mA}$

54. $A_{v(\text{max})} = (1800\ \mu\text{S})(2.2\text{ k}\Omega) = \mathbf{3.96}$

Advanced Problems

55. $R_{d(\text{min})} = 1.0\text{ k}\Omega \parallel 4\text{ k}\Omega = 800\ \Omega$

$A_{v(\text{min})} = (2.5\text{ mS})(800\ \Omega) = \mathbf{2.0}$

$R_{d(\text{max})} = 1.0\text{ k}\Omega \parallel 10\text{ k}\Omega = 909\ \Omega$

$A_{v(\text{min})} = (7.5\text{ mS})(909\ \Omega) = \mathbf{6.82}$

56. $I_{\text{DSS(typ)}} = 2.9\text{ mA}$

$$R_{\text{D}} + R_{\text{S}} = \frac{12\text{ V}}{2.9\text{ mA}} = 4.14\text{ k}\Omega$$

$$\frac{1}{g_m} = \frac{1}{2300\ \mu\text{S}} = 435\ \Omega$$

If $R_S = 0\ \Omega$, then $R_D \cong 4\text{ k}\Omega\,(3.9\text{ k}\Omega\text{ standard})$

$A_v = (2300\ \mu\text{S})(3.9\text{ k}\Omega) = \mathbf{8.97}$

$V_{\text{DS}} = 24\text{ V} - (2.9\text{ mA})(3.9\text{ k}\Omega) = 24\text{ V} - 11.3\text{ V} = \mathbf{12.7\ V}$

The circuit is a common-source zero-biased amplifier with a drain resistor of $3.9\text{ k}\Omega$

57. To maintain $V_{DS} = 12$ V for the range of I_{DSS} values:

For $I_{DSS(min)} = 2$ mA

$$R_D = \frac{12\text{ V}}{2\text{ mA}} = 6\text{ k}\Omega$$

For $I_{DSS(max)} = 6$ mA

$$R_D = \frac{12\text{ V}}{6\text{ mA}} = 2\text{ k}\Omega$$

To maintain $A_v = 9$ for the range of $g_m(y_{fs})$ values:

For $g_{m(min)} = 1500\ \mu$S

$$R_D = \frac{9}{1500\ \mu\text{S}} = 6\text{ k}\Omega$$

For $g_{m(max)} = 3000\ \mu$S

$$R_D = \frac{9}{3000\ \mu\text{S}} = 3\text{ k}\Omega$$

A drain resistance consisting of a $2.2\text{ k}\Omega$ fixed resistor in series with a $5\text{ k}\Omega$ variable resistor will provide more than sufficient range to maintain a gain of 9 over the specified range of g_m values. The dc voltage at the drain will vary with adjustment and depends on I_{DSS}. The circuit cannot be modified to maintain both $V_{DS} = 12\text{ V}$ and $A_v = 9$ over the full range of transistor parameter values. See Figure 9-3.

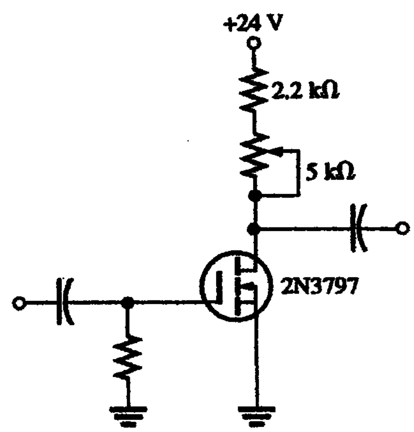

Figure 9-3

Multisim Troubleshooting Problems

58. Drain-source shorted

59. C_2 open

60. C_1 open

61. R_s shorted

62. Drain-source open

63. R_1 open

64. R_D open

65. R_2 open

66. C_2 open

Chapter 10
Amplifier Frequency Response

Section 10-1 Basic Concepts

1. (a) Parasitic capacitance affects the high-frequency response.

(b) A designer can choose a transistor with a lower internal capacitance, lower the gain to reduce the Miller effect, or change the circuit to use a noninverting amplifier.

2. At sufficiently high frequencies, the reactances of the coupling capacitors become very small, and the capacitors appear effectively as shorts; thus, negligible signal voltage is dropped across them.

3. BJT: C_{be}, C_{bc}, and C_{ce}

FET: C_{gs}, C_{gd}, and C_{ds}

4. Low-frequency response: C_1, C_2, and C_3

High-frequency response: C_{bc}, C_{be}, and C_{ce}

5. $$V_{\text{E}} \cong \left(\frac{R_2}{R_1 + R_2}\right)V_{\text{CC}} - 0.7\text{ V} = \left(\frac{4.7\text{ k}\Omega}{37.7\text{ k}\Omega}\right)20\text{ V} - 0.7\text{ V} = 1.79\text{ V}$$

$$I_{\text{E}} = \frac{V_{\text{E}}}{R_{\text{E}}} = \frac{1.79\text{ V}}{560\ \Omega} = 3.2\text{ mA}$$

$$r_e' = \frac{25\text{ mV}}{3.2\text{ mA}} = 7.8\ \Omega$$

$$A_v = \frac{R_c}{r_e'} = \frac{2.2\text{ k}\Omega \parallel 5.6\text{ k}\Omega}{7.8\ \Omega} = 202$$

$$C_{in(miller)} = C_{bc}(A_v + 1) = 4\text{ pE}(202 + 1) = \mathbf{812\ pF}$$

6. $$C_{out(miller)} = C_{bc}\left(\frac{A_v + 1}{A_v}\right) = 4\text{ pF}\left(\frac{203}{202}\right) = \mathbf{4\ pF}$$

7. $I_{\text{D}} = 3.36$ mA using Eq. 9–2 and a programmable calculator.

$$V_{\text{GS}} = -(3.36\text{ mA})(1.0\text{ k}\Omega) = -3.36\text{ V}$$

$$g_{m0} = \frac{2(10\text{ mA})}{8\text{ V}} = 2.5\text{ mS}$$

$$g_m = (2.5\text{ mS})\left(1 - \frac{3.36\text{ V}}{8\text{ V}}\right) = 1.45\text{ mS}$$

$$A_v = g_m R_d = (1.45 \text{ mS})(1.0 \text{ k}\Omega \| 10 \text{ k}\Omega) = 1.32$$

$$C_{gd} = C_{rss} = 3 \text{ pF}$$

$$C_{in(miller)} = C_{gd}(A_v + 1) = 3 \text{ pE}(2.32) = \mathbf{6.95\ pF}$$

$$C_{out(miller)} = C_{gd}\left(\frac{A_v + 1}{A_v}\right) = 3 \text{ pF}\left(\frac{2.32}{1.32}\right) = \mathbf{5.28\ pF}$$

Section 10-2 The Decibel

8. $$A_p = \frac{P_{out}}{P_{in}} = \frac{5 \text{ W}}{0.5 \text{ W}} = 10$$

$$A_{p(\text{dB})} = 10 \log\left(\frac{P_{out}}{P_{in}}\right) = 10 \log 10 = \mathbf{10\ dB}$$

9. $$V_{in} = \frac{V_{out}}{A_v} = \frac{1.2 \text{ V}}{50} = \mathbf{24\ mV\ rms}$$

$$A_{v(\text{dB})} = 20 \log(A_v) = 20 \log 50 = \mathbf{34.0\ dB}$$

10. The gain reduction is $20 \log\left(\frac{25}{65}\right) = \mathbf{-8.3\ dB}$

11. (a) $10 \log\left(\frac{2 \text{ mW}}{1 \text{ mW}}\right) = \mathbf{3.01\ dBm}$

(b) $10 \log\left(\frac{1 \text{ mW}}{1 \text{ mW}}\right) = \mathbf{0\ dBm}$

(c) $10 \log\left(\frac{4 \text{ mW}}{1 \text{ mW}}\right) = \mathbf{6.02\ dBm}$

(d) $10 \log\left(\frac{0.25 \text{ mW}}{1 \text{ mW}}\right) = \mathbf{-6.02\ dBm}$

12. $$V_{\text{B}} = \left(\frac{4.7 \text{ k}\Omega}{37.7 \text{ k}\Omega}\right) 20 \text{ V} = 1.79 \text{ V}$$

$$I_{\text{E}} = \frac{1.79 \text{ V}}{560\ \Omega} = 3.20 \text{ mA}$$

$$r_e' = \frac{25 \text{ mV}}{3.2 \text{ mA}} = 7.81\ \Omega$$

$$A_v = \frac{5.6 \text{ k}\Omega \| 2.2 \text{ k}\Omega}{7.81\ \Omega} = 202$$

$A_{v(\text{dB})} = 20 \log(202) = \mathbf{46.1\ dB}$

At the critical frequencies,

$A_{v(\text{dB})} = 46.1\ \text{dB} - 3\ \text{dB} = \mathbf{43.1\ dB}$

Section 10-3 Low-Frequency Amplifier Response

13. (a) $f_c = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi(100\ \Omega)(5\ \mu\text{F})} = \mathbf{318\ Hz}$

(b) $f_c = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi(1.0\ \text{k}\Omega)(0.1\ \mu\text{F})} = \mathbf{1.59\ kHz}$

14. $R_{\text{IN(BASE)}} = \beta_{\text{DC}} R_{\text{E}} = 12.5\ \text{k}\Omega$

$$V_{\text{E}} = \left(\frac{R_2 \parallel R_{\text{IN(BASE)}}}{R_1 + R_2 \parallel R_{\text{IN(BASE)}}}\right) 9\ \text{V} - 0.7\ \text{V} = \left(\frac{4.7\ \text{k}\Omega \parallel 12.5\ \text{k}\Omega}{12\ \text{k}\Omega + 4.7\ \text{k}\Omega \parallel 12.5\ \text{k}\Omega}\right) 9\ \text{V} - 0.7\ \text{V} = 1.3\ \text{V}$$

$$I_{\text{E}} = \frac{V_{\text{E}}}{R_{\text{E}}} = \frac{1.3\ \text{V}}{100\ \Omega} = 13\ \text{mA}$$

$$r'_e = \frac{25\ \text{mV}}{13\ \text{mA}} = 1.92\ \Omega$$

$$R_{in(base)} = \beta_{ac} r'_e = (125)(1.92\ \Omega) = 240\ \Omega$$

$$R_{in} = 50\ \Omega + R_{in(base)} \parallel R_1 \parallel R_2 = 50\ \Omega + 240\ \Omega \parallel 12\ \text{k}\Omega \parallel 4.7\ \text{k}\Omega = 274\ \Omega$$

For the input circuit:

$$f_c = \frac{1}{2\pi R_{in} C_1} = \frac{1}{2\pi(274\ \Omega)(1\ \mu\text{F})} = \mathbf{581\ Hz}$$

For the output circuit:

$$f_c = \frac{1}{2\pi(R_{\text{C}} + R_L)C_3} = \frac{1}{2\pi(900\ \Omega)(1\ \mu\text{F})} = \mathbf{177\ Hz}$$

For the bypass circuit:

$$R_{\text{TH}} = R_1 \parallel R_2 \parallel R_s = 12\ \text{k}\Omega \parallel 4.7\ \text{k}\Omega \parallel 50\ \Omega \cong 49.3\ \Omega$$

$$f_c = \frac{1}{2\pi\left(r'_e + R_{\text{RH}} / \beta_{\text{DC}} \parallel R_{\text{E}}\right)C_2} = \frac{1}{2\pi(2.31\ \Omega)(10\ \mu\text{F})} = \mathbf{6.89\ kHz}$$

$$A_v = \frac{R_{\text{C}} \parallel R_L}{r'_e} = \frac{220\ \Omega \parallel 680\ \Omega}{1.92\ \Omega} = 86.6$$

$A_{v(\text{dB})} = 20 \log(86.6) = 38.8\ \text{dB}$

The **bypass circuit** produces the dominant low critical frequency. See Figure 10-1.

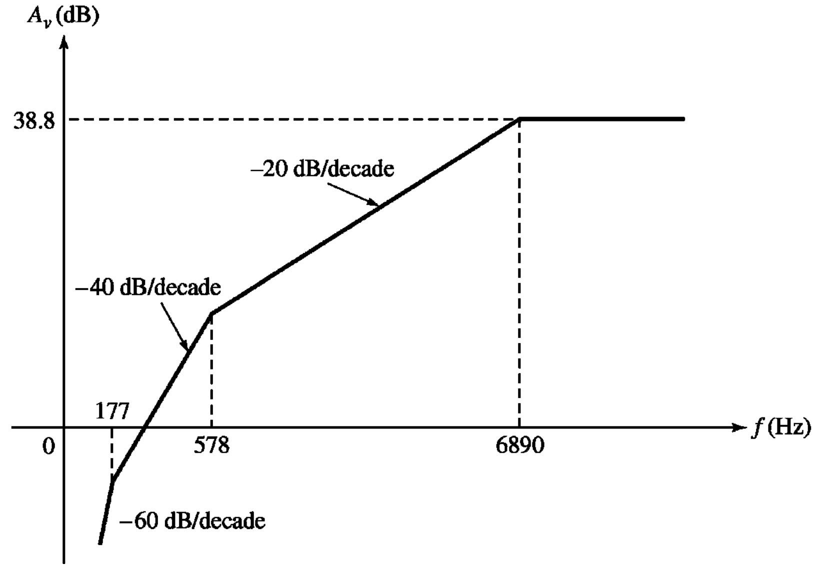

Figure 10-1

15. From Problem 14:

$A_{v(mid)} = 86.6$

$A_{v(mid)}$ (dB) = 38.8 dB

For the input RC circuit: $f_c = 578$ Hz

For the output RC circuit: $f_c = 177$ Hz

For the bypass RC circuit: $f_c = 6.89$ kHz

The f_c of the bypass circuit is the dominant low critical frequency.

At $f = f_c = 6.89$ kHz:

$A_v = A_{v(mid)} - 3\text{ dB} = 38.8\text{ dB} - 3\text{ dB} = \mathbf{35.8\text{ dB}}$

At $f = 0.1f_c$:

$A_v = 38.8\text{ dB} - 20\text{ dB} = \mathbf{18.8\text{ dB}}$

At $10f_c$ (neglecting any high-frequency effects):

$A_v = A_{v(mid)} = \mathbf{38.8\text{ dB}}$

16. At $f = f_c = X_C = R$

$$\theta = \tan^{-1}\left(\frac{X_C}{R}\right) = \tan^{-1}(-1) = \mathbf{45°}$$

At $f = 0.1\,f_c$, $X_C = 10R$.

$$\theta = \tan^{-1}(10) = \mathbf{84.3°}$$

At $f = 10\,f_c$, $X_C = 0.1R$.

$$\theta = \tan^{-1}(0.1) = \mathbf{5.7°}$$

17. $$R_{in(gate)} = \left|\frac{V_{GS}}{I_{GSS}}\right| = \left|\frac{-10\text{ V}}{50\text{ nA}}\right| = 200\text{ M}\Omega$$

$$R_{in} = R_G \parallel R_{in(gate)} = 10\text{ M}\Omega \parallel 200\text{ M}\Omega = 9.52\text{ M}\Omega$$

For the input circuit:

$$f_c = \frac{1}{2\pi R_{in} C_1} = \frac{1}{2\pi(9.52\text{ M}\Omega)(0.005\ \mu\text{F})} = \mathbf{3.34\ Hz}$$

For the output circuit:

$$f_c = \frac{1}{2\pi(R_D + R_L)C_2} = \frac{1}{2\pi(560\ \Omega + 10\text{ k}\Omega)(0.005\ \mu\text{F})} = \mathbf{3.01\ kHz}$$

The **output circuit is dominant**. See Figure 10-2. (A_v is determined in Problem 18.)

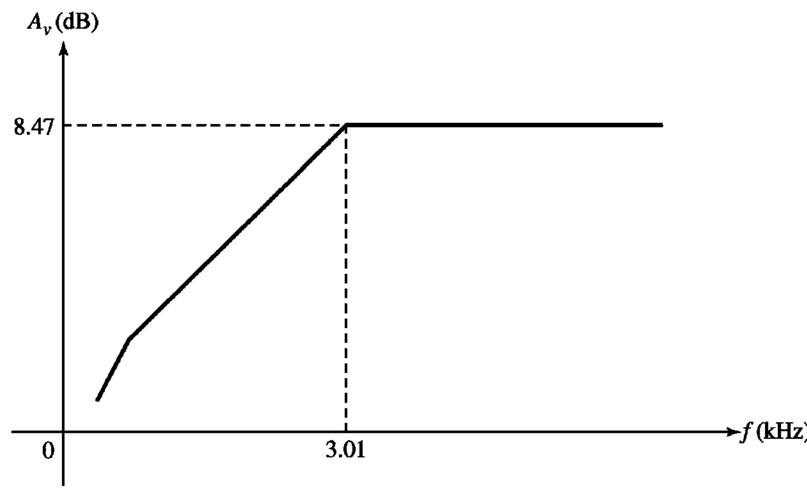

Figure 10-2

18. $$g_m = g_{m0} = \frac{2(15\text{ mA})}{6\text{ V}} = 5\text{ mS}$$

$$A_{v(mid)} = g_m\left(R_D \| R_L\right) = 5\text{ mS}(560\ \Omega \parallel 10\text{ k}\Omega) = 2.65$$

$$A_{v(mid)}(\text{dB}) = 8.47\text{ dB}$$

At f_c:

$$A_v = 8.47\text{ dB} - 3\text{ dB} = \mathbf{5.47\ dB}$$

At $0.1f_c$:

$$A_v = 8.47\text{ dB} - 20\text{ dB} = \mathbf{-11.5\ dB}$$

At $10f_c$:

$A_v = A_{v(mid)} = \mathbf{8.47\ dB}$ (if $10f_c$ is still in midrange)

Section 10-4 High-Frequency Amplifier Response

19. From Problems 14 and 15:

$r'_e = 1.92\ \Omega$ and $A_{v(mid)} = 86.6$

Input circuit:

$$C_{in(miller)} = C_{bc}(A_v + 1) = 10\text{ pF}(87.6) = 876\text{ pF}$$

$$C_{tot} = C_{be} + C_{in(miller)} = 25\text{ pF} + 876\text{ pF} = 901\text{ pF}$$

$$f_c = \frac{1}{2\pi\left(R_s \parallel R_1 \parallel R_2 \parallel \beta_{ac} r'_e\right) C_{tot}} = \frac{1}{2\pi\left(50\ \Omega \parallel 12\text{ k}\Omega \parallel 4.7\text{ k}\Omega \parallel 240\ \Omega\right) 901\text{ pF}} = \mathbf{4.32\ MHz}$$

Output circuit:

$$C_{out(miller)} = C_{bc}\left(\frac{A_v + 1}{A_v}\right) = 10\text{ pF}\left(\frac{87.6}{86.6}\right) = 10.1\text{ pF}$$

$$f_c = \frac{1}{2\pi R_c C_{out(miller)}} = \frac{1}{2\pi(166\ \Omega)(10.1\text{ pF})} = \mathbf{94.9\ MHz}$$

Therefore, the dominant high critical frequency is determined by the input circuit:

$f_c = 4.32$ MHz. See Figure 10-3.

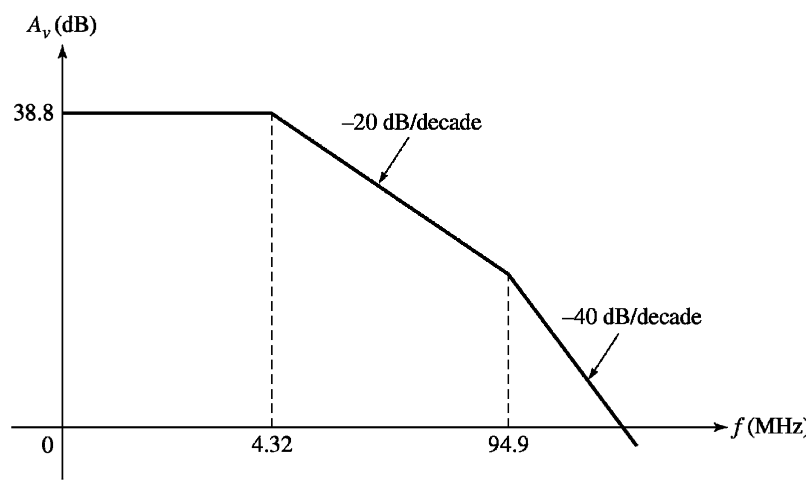

Figure 10-3

20. At $f = 0.1 f_c = 458$ kHz:

$A_v = A_{v(mid)} = \mathbf{38.8\ dB}$

At $f = f_c = 4.58$ MHz:

$A_v = A_{v(mid)} - 3\text{ dB} = 38.8\text{ dB} - 3\text{ dB} = \mathbf{35.8\ dB}$

At $f = 10 f_c = 45.8$ MHz:

$A_v = A_{v(mid)} - 20\text{ dB} = 38.8\text{ dB} - 20\text{ dB} = \mathbf{18.8\ dB}$

At $f = 100 f_c = 458$ MHz:

The roll-off rate changes to –40 dB/decade at f = 94.6 MHz. So, for frequencies from 45.8 MHz to 94.6 MHz, the roll-off rate is –20 dB/decade and above 94.6 MHz it is –40 dB/decade.

The change in frequency from 45.8 MHz to 94.6 MHz represents

$$\frac{94.6\text{ MHz} - 45.8\text{ MHz}}{458\text{ MHz} - 45.8\text{ MHz}} \times 100\% = 11.8\%$$

So, for 11.8% of the decade from 45.8 MHz to 458 MHz, the roll-off rate is –20 dB/decade, and for the remaining 88.2% of the decade, the roll-off rate is –40 dB/decade.

$A_v = 18.8\text{ dB} - (0.118)(20\text{ dB}) - (0.882)(40\text{ dB}) = 18.8\text{ dB} - 2.36\text{ dB} - 35.3\text{ dB} = \mathbf{-18.9\ dB}$

21. $C_{gd} = C_{rss} = 4$ pF

$C_{gs} = C_{iss} - C_{rss} = 10\text{ pF} - 4\text{ pF} = 6\text{ pF}$

Input circuit:

$C_{in(miller)} = C_{gd}(A_v + 1) = 4\text{ pF}(2.65 + 1) = 14.6\text{ pF}$

$C_{tot} = C_{gs} + C_{in(miller)} = 6\text{ pF} + 14.6\text{ pF} = 20.6\text{ pF}$

$$f_c = \frac{1}{2\pi R_s C_{tot}} = \frac{1}{2\pi(600\ \Omega)(20.6\text{ pF})} = \mathbf{12.9\ MHz}$$

Output circuit:

$$C_{out(miller)} = C_{gd}\left(\frac{A_v + 1}{A_v}\right) = 4\text{ pF}\left(\frac{2.65 + 1}{2.65}\right) = 5.51\text{ pF}$$

$$f_c = \frac{1}{2\pi R_d C_{out(miller)}} = \frac{1}{2\pi(530\ \Omega)(5.51\text{ pF})} = \mathbf{54.5\ MHz}$$

The input circuit is dominant.

22. From Problem 21: For the input circuit, $f_c = 12.9$ MHz and for the output circuit, $f_c = 54.5$ MHz.

The dominant critical frequency is 12.9 MHz.

At $f = 0.1 f_c = 1.29$ MHz: $A_v = A_{v(mid)} = \mathbf{8.47\ dB}, \theta = \mathbf{0°}$

At $f = f_c = 1.29$ MHz: $A_v = A_{v(mid)} - 3\text{ dB} = 8.47\text{ dB} - 3\text{ dB} = \mathbf{5.47\ dB}, \theta = \tan^{-1}(1) = \mathbf{45°}$

At $f = 10 f_c = 129$ MHz:

From 12.9 MHz to 54.5 MHz the roll-off is –20 dB/decade. From 54.5 MHz to 129 MHz the roll-off is –40 dB/decade.

The change in frequency from 12.9 MHz to 54.5 MHz represents

$$\frac{54.5\text{ MHz} - 12.9\text{ MHz}}{129\text{ MHz} - 12.9\text{ MHz}} \times 100\% = 35.8\%$$

So, for 35.8% of the decade, the roll-off rate is –20 dB/decade, and for 64.2% of the decade, the rate is –40 dB/decade.

$A_v = 5.47\text{ dB} - (0.358)(20\text{ dB}) - (0.642)(40\text{ dB}) = \mathbf{-27.4\ dB}$

At $f = 100 f_c = 1290\text{ MHz}$: $A_v = -27.4\text{ dB} - 40\text{ dB} = \mathbf{-67.4\ dB}$

Section 10-5 Total Amplifier Frequency Response

23. $f_{cl} = \mathbf{136\ Hz}$

$f_{cu} = \mathbf{8\ kHz}$

24. From Problems 14 and 19:

$f_{cu} = 4.32\text{ MHz}$ and $f_{cl} = 6.89\text{ kHz}$

$BW = f_{cu} - f_{cl} = 4.32\text{ MHz} - 6.89\text{ kHz} = \mathbf{4.313\ MHz}$

25. $f_{tot} = (BW)A_{v(mid)}$

$$BW = \frac{f_{tot}}{A_{v(mid)}} = \frac{200\text{ MHz}}{38} = \mathbf{5.26\ MHz}$$

Therefore, $f_{cu} \cong BW = \mathbf{5.26\ MHz}$

26. 6 dB/octave roll-off:

At $2f_{cu}$: $A_v = 50\text{ dB} - 6\text{ dB} = \mathbf{44\ dB}$

At $4f_{cu}$: $A_v = 50\text{ dB} - 12\text{ dB} = \mathbf{38\ dB}$

20 dB/decade roll-off:

At $10f_{cu}$: $A_v = 50\text{ dB} - 20\text{ dB} = \mathbf{30\ dB}$

Section 10-6 Frequency Response of Multistage Amplifiers

27. Dominant $f'_{cl} = \mathbf{230\ Hz}$

Dominant $f'_{cu} = \mathbf{1.2\ MHz}$

28. $BW = 1.2\text{ MHz} - 230\text{ Hz} \cong \mathbf{1.2\ MHz}$

29. $f'_{cl} = \dfrac{400\text{ Hz}}{\sqrt{2^{1/2}-1}} = \dfrac{400\text{ Hz}}{0.643} = 622\text{ Hz}$

$f'_{cu} = (800\text{ kHz})\sqrt{2^{1/2}-1} = 0.643(800\text{ kHz}) = 515\text{ kHz}$
$BW = 515\text{ kHz} - 622\text{ Hz} \cong \mathbf{514\text{ kHz}}$

30. $f'_{cl} = \dfrac{50\text{ Hz}}{\sqrt{2^{1/3}-1}} = \dfrac{50\text{ Hz}}{0.510} = \mathbf{98.1\text{ Hz}}$

31. $f'_{cl} = \dfrac{125\text{ Hz}}{\sqrt{2^{1/2}-1}} = \dfrac{125\text{ Hz}}{0.643} = 194\text{ Hz}$

$f'_{cu}\, 2.5\text{ MHz}$

$BW = 2.5\text{ MHz} - 194\text{ Hz} \cong \mathbf{2.5\text{ MHz}}$

Section 10-7 Frequency Response Measurements

32. $f_{cl} = \dfrac{0.35}{t_f} = \dfrac{0.35}{1\text{ ms}} = \mathbf{350\text{ Hz}}$

$f_{cu} = \dfrac{0.35}{t_r} = \dfrac{0.35}{20\text{ ns}} = \mathbf{17.5\text{ MHz}}$

33. Increase the frequency until the output voltage drops to 3.54 V (3 dB below the midrange output voltage). This is the upper critical frequency.

34. $t_r \cong 3\text{ div} \times 5\ \mu\text{s/div} = 15\ \mu\text{s}$

$t_f \cong 6\text{ div} \times 0.1\text{ ms/div} = 600\ \mu\text{s}$

$f_{cl} = \dfrac{0.35}{t_f} = \dfrac{0.35}{600\ \mu\text{s}} = 583\text{ Hz}$

$f_{cu} = \dfrac{0.35}{t_r} = \dfrac{0.35}{15\ \mu\text{s}} = 23.3\text{ kHz}$

$BW = 23.3\text{ kHz} - 583\text{ Hz} = \mathbf{22.7\text{ kHz}}$

Device Application Problems

35. Q_1 stage:

$$f_{cl(input)} = \frac{1}{2\pi(R_1 \parallel R_2 \parallel \beta_{ac}R_4)C_1} = \frac{1}{2\pi(62.3\text{ k}\Omega)1\ \mu\text{F}} = 2.55\text{ Hz}$$

$$f_{cl(bypass)} = \frac{1}{2\pi R_4 C_2} = \frac{1}{2\pi(1\text{ k}\Omega)10\ \mu\text{F}} = 15.9\text{ Hz}$$

$$f_{cl(output)} = \frac{1}{2\pi(R_5 + R_6 \parallel R_7 \parallel \beta_{ac}(R_9 + R_{10})C_3} = \frac{1}{2\pi(37\text{ k}\Omega)1\ \mu\text{F}} = 4.30\text{ Hz}$$

Q_2 stage:

$$f_{cl(input)} = \frac{1}{2\pi(R_5 \parallel R_6 \parallel R_7 \parallel \beta_{ac}(R_9 + R_{10})C_3} = \frac{1}{2\pi(8.9\text{ k}\Omega)1\ \mu\text{F}} = 17.9\text{ Hz}$$

$$f_{cl(bypass)} = \frac{1}{2\pi\left(R_9 + \dfrac{R_6 \parallel R_7}{\beta_{ac}}\right)C_4} = \frac{1}{2\pi(208\ \Omega)100\ \mu\text{F}} = 0.006\text{ Hz}$$

$$f_{cl(output)} = \frac{1}{2\pi\left(R_8 + R_L\right)C_5} = \frac{1}{2\pi(35.8\text{ k}\Omega)1\ \mu\text{F}} = 4.45\text{ Hz}$$

The dominant critical frequency of **15.9 Hz** is set by the Q_1 bypass circuit.

36. Changing to 1 μF coupling capacitors does not significantly affect the overall bandwidth because the upper critical frequency is much greater than the dominant lower critical frequency.

37. Increasing the load resistance on the output of the second stage has no effect on the dominant lower critical frequency because the critical frequency of the output circuit will decrease and the critical frequency of the first stage input circuit will remain dominant.

38. The Q_1 stage bypass circuit set the dominant critical frequency.

$$f_{cl(bypass)} = \frac{1}{2\pi R_4 C_2} = \frac{1}{2\pi(1\text{ k}\Omega)10\ \mu\text{F}} = 15.9\text{ Hz}$$

This frequency is not dependent on β_{ac} and is not affected.

Datasheet Problems

39. $C_{in(tot)} = (25 + 1)4\text{ pF} + 8\text{ pF} = \mathbf{112\ pF}$

40. $BW_{\min} = \dfrac{f_T}{A_{v(mid)}} = \dfrac{300\text{ MHz}}{50} = \mathbf{6\ MHz}$

41. $C_{gd} = C_{rss} = \mathbf{1.3\ pF}$

$C_{gs} = C_{iss} - C_{rss} = 5\text{ pF} - 1.3\text{ pF} = \mathbf{3.7\ pF}$

$C_{ds} = C_d - C_{rss} = 5\text{ pF} - 1.3\text{ pF} = \mathbf{3.7\ pF}$

Advanced Problems

42. From Problem 12: $r_e' = 7.81\ \Omega$ and $I_E = 3.2\text{ mA}$

$V_C \cong 20\text{ V} - (3.2\text{ mA})(2.2\text{ k}\Omega) = 13\text{ V dc}$

The maximum peak output signal can be approximately 6 V.

The maximum allowable gain for the two stages is

$$A_{v(\max)} = \frac{6\text{ V}}{1.414(10\text{ mV})} = 424$$

For stage 1:

$$R_c = 2.2\text{ k}\Omega \parallel 33\text{ k}\Omega \parallel 4.7\text{ k}\Omega \parallel (150)(7.81\ \Omega) = 645\ \Omega$$

$$A_{v1} = \frac{645\ \Omega}{7.81\ \Omega} = 82.6$$

For stage 2:

$$R_c = 2.2\text{ k}\Omega \parallel 5.6\text{ k}\Omega = 1.58\text{ k}\Omega$$

$$A_{v1} = \frac{1.58\text{ k}\Omega}{7.81\ \Omega} = 202$$

$$A_{v(tot)} = (82.6)(202) = 16{,}685$$

The amplifier will **not operate linearly** with a 10 mV rms input signal.

The gains of both stages can be reduced or the gain of the second stage only can be reduced.

One approach is leave the gain of the first stage as is and bypass a portion of the emitter resistance in the second stage to achieve a gain of 424/82.6 = 5.13.

$$A_v = \frac{R_c}{R_e + r_e'} = 5.13$$

$$R_e = \frac{R_c - 5.13 r_e'}{5.13} = \frac{1.58\text{ k}\Omega - 40.1\ \Omega}{5.13} = 300\ \Omega$$

Modification: Replace the 560 Ω emitter resistor in the second stage with an unbypassed 300 Ω resistor and a bypassed 260 Ω resistor (closest standard value is 270 Ω).

43. From Problems 17, 18, and 21:

$$C_{tot} = C_{gs} + C_{in(miller)} = 20.6\text{ pF}$$

$$C_{out(miller)} = 4\text{ pF}\left(\frac{2.65+1}{2.65}\right) = 5.51\text{ pF}$$

Stage 1:

$$f_{cl(in)} = \frac{1}{2\pi R_{in}C_1} = \frac{1}{2\pi(9.52\text{ M}\Omega)(0.005\ \mu\text{F})} = 3.34\text{ Hz}$$

$$f_{cl(out)} = \frac{1}{2\pi(9.52\text{ M}\Omega)(0.005\ \mu\text{F})} = 3.34\text{ Hz}\ \text{ since }\ R_{in(2)} >> 560\,\Omega$$

$$f_{cu(in)} = \frac{1}{2\pi(600\ \Omega)(20.6\text{ pF})} = 12.9\text{ MHz}$$

$$f_{cu(out)} = \frac{1}{2\pi(560\ \Omega)(20.6\text{ pF} + 5.51\text{ pF})} = 10.9\text{ MHz}$$

Stage 2:

$$f_{cl(in)} = \frac{1}{2\pi R_{in}C_1} = \frac{1}{2\pi(9.52\text{ M}\Omega)(0.005\ \mu\text{F})} = 3.34\text{ Hz}$$

$$f_{cl(out)} = \frac{1}{2\pi(10.6\text{ k}\Omega)(0.005\ \mu\text{F})} = 3.01\text{ kHz}$$

$$f_{cu(in)} = \frac{1}{2\pi(560\ \Omega)(20.6\text{ pF} + 5.51\text{ pF})} = 10.9\text{ MHz}$$

$$f_{cu(out)} = \frac{1}{2\pi(560\ \Omega \parallel 10\text{ k}\Omega)(5.51\text{ pF})} = 54.5\text{ MHz}$$

Overall:

$f_{cl(in)} = 3.34\text{ kHz}$ and $f_{cu(in)} = 10.9\text{ MHz}$

$BW \cong \mathbf{10.9\ MHz}$

44. $R_{in(1)} = 22\text{ k}\Omega \parallel (100)(320\ \Omega) = 13\text{ k}\Omega$

$$V_{\text{B}(1)} = \left(\frac{13\text{ k}\Omega}{113\text{ k}\Omega}\right)12\text{ V} = 1.38,\quad V_{\text{E}(1)} = 0.681\text{ V}$$

$$I_{\text{E}(1)} = \frac{0.681\text{ V}}{320\ \Omega} = 2.13\text{ mA},\quad r_e' = 11.7\ \Omega$$

$$R_{c(1)} = 4.7\text{ k}\Omega \parallel 33\text{ k}\Omega \parallel 22\text{ k}\Omega \parallel (100)(100\ \Omega) = 2.57\text{ k}\Omega$$

$$A_{v(1)} = \frac{2.57\text{ k}\Omega}{112\ \Omega} = 23$$

$$R_{in(2)} = 22\text{ k}\Omega \parallel (100)(1010\ \Omega) = 18\text{ k}\Omega$$

$$V_{\text{B}(2)} = \left(\frac{18\text{ k}\Omega}{51\text{ k}\Omega}\right)12\text{ V} = 4.24,\quad V_{\text{E}(1)} = 3.54\text{ V}$$

$$I_{\text{E}(2)} = \frac{3.54\text{ V}}{1.01\text{ k}\Omega} = 3.51\text{ mA},\quad r_e' = 7.13\ \Omega$$

$$R_{c(2)} = 3\text{ k}\Omega \parallel 10\text{ k}\Omega = 2.31\text{ k}\Omega$$

$$A_{v(2)} = \frac{2.31\text{ k}\Omega}{107.13\ \Omega} = 24\text{ maximum}$$

$$A_{v(2)} = \frac{2.31\text{ k}\Omega}{101\text{ k}\Omega + 7.13\ \Omega} = 2.27\text{ minimum}$$

$$A_{v(tot)} = (23)(24) = 552\text{ maximum}$$

$$A_{v(tot)} = (23)(2.27) = 52.3\text{ minimum}$$

This is a bit high, so adjust $R_{c(1)}$ to 3 kΩ, then

$$A_{v(1)} = \frac{3\text{ k}\Omega \parallel 22\text{ k}\Omega \parallel 33\text{ k}\Omega \parallel 101\text{ k}\Omega}{112\ \Omega} = 21.4$$

Now,

$$A_{v(tot)} = (21.3)(24) = \mathbf{513}\text{ maximum}$$

$$A_{v(tot)} = (21.3)(2.27) = \mathbf{48.5}\text{ minimum}$$

Thus, A_v is within 3% of the desired specifications.

Frequency response for stage 1:

$$R_{in} = 22\text{ k}\Omega \parallel 100\text{ k}\Omega \parallel 32\text{ k}\Omega = 11.5\text{ k}\Omega$$

$$f_{cl(in)} = \frac{1}{2\pi(11.5\text{ k}\Omega)(10\ \mu\text{F})} = 1.38\text{ Hz}$$

$$R_{emitter} = 220\ \Omega \parallel (100\ \Omega + 11.7\ \Omega + (22\text{ k}\Omega \parallel 100\text{ k}\Omega / 100 = 125\ \Omega$$

$$f_{cl(bypass)} = \frac{1}{2\pi(125\ \Omega)(100\ \mu\text{F})} = 12.7\text{ Hz}$$

$$R_{out} = 3\text{ k}\Omega + (33\text{ k}\Omega \parallel 22\text{ k}\Omega \parallel (100)(107\ \Omega)) = 8.91\text{ k}\Omega$$

$$f_{cl(out)} = \frac{1}{2\pi(8.91\text{ k}\Omega)(10\ \mu\text{F})} = 1.79\text{ Hz}$$

Frequency response for stage 2:

$f_{cl(in)} = 1.79$ Hz (same as $f_{cl(out)}$ for stage 1)

$R_{out} = 3\text{ k}\Omega + 10\text{ k}\Omega = 13\text{ k}\Omega$

$$f_{cl(out)} = \frac{1}{2\pi(13\text{ k}\Omega)(10\ \mu\text{F})} = 1.22\text{ Hz}$$

This means that $C_{\text{E(2)}}$ is the frequency limiting capacitance.

$R_{emitter} 910\ \Omega \,\|\, (100\ \Omega + 7\ \Omega + (22\text{ k}\Omega \,\|\, 33\text{ k}\Omega \,\|\, 3\text{ k}\Omega)/100) = 115\ \Omega$

For $f'_{cl} = 1$ kHz:

$$C_{\text{E(2)}} = \frac{1}{2\pi(115\ \Omega)(1\text{ kHz})} = 1.38\ \mu\text{F}$$

1.5 μF is the closest standard value and gives

$$f_{cl(bypass)} = \frac{1}{2\pi(115\ \Omega)(1.5\ \mu\text{F})} = \mathbf{922\ Hz}$$

This value can be moved closer to 1 kHz by using additional parallel bypass capacitors in stage 2 to fine-tune the response.

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 45 through 48 are available from the Instructor Resource Center. See Chapter 2 for instructions. The faults in the circuit files may be accessed using the password *book* (all lowercase).

45. R_{C} open

46. Output capacitor open

47. R_2 open

48. Drain-source shorted

Chapter 11
Thyristors

Section 11-1 The Four-Layer Diode

1. $V_A = V_{BE} + V_{CE(sat)} = 0.7\text{ V} + 0.2\text{ V} = 0.9\text{ V}$

$V_{R_S} = V_{BIAS} - V_A = 25\text{ V} - 0.9\text{ V} = 24.1\text{ V}$

$$I_A = \frac{V_{R_S}}{R_S} = \frac{24.1\text{ V}}{1.0\text{ k}\Omega} = \mathbf{24.1\ mA}$$

2. (a) $R_{AK} = \dfrac{V_{AK}}{I_A} = \dfrac{15\text{ V}}{1\,\mu\text{A}} = \mathbf{15\ M\Omega}$

(b) From 15 V to 50 V for an increase of 35 V.

Section 11-2 The Silicon-Controlled Rectifier (SCR)

3. See Section 11-2 in the textbook.

4. Neglecting the SCR voltage drop,

$$R_{max} = \frac{30\text{ V} - 0.7\text{ V}}{10\text{ mA}} = \mathbf{2.93\ k\Omega}$$

5. When the switch is closed, the battery V_2 causes illumination of the lamp. The light energy causes the LASCR to conduct and thus energize the relay. When the relay is energized, the contacts close and 115 V ac are applied to the motor.

6. See Figure 11-1.

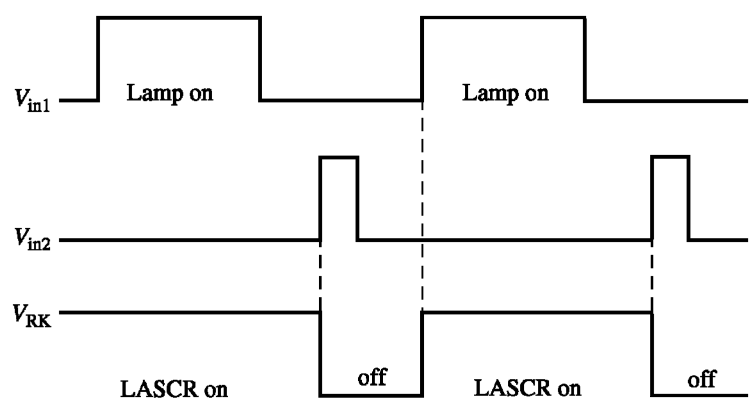

Figure 11-1

Section 11-3 SCR Applications

7. Add a transistor to provide inversion of the negative half-cycle in order to obtain a positive gate trigger.

8. D_1 and D_2 are full-wave rectifier diodes.

9. See Figure 11-2.

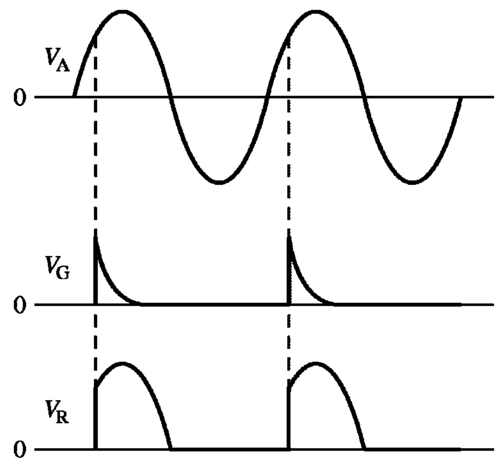

Figure 11-2

Section 11-4 The Diac and Triac

10. $V_{in(p)} = 1.414V_{in(rms)} = 1.414(25\text{ V}) = 35.4\text{ V}$

$$I_p = V_{in(p)} = \frac{35.35\text{ V}}{1.0\text{ k}\Omega} = 35.4\text{ mA}$$

$$\text{Current at breakover} = \frac{20\text{ V}}{1.0\text{ k}\Omega} = 20\text{ mA}$$

See Figure 11-3.

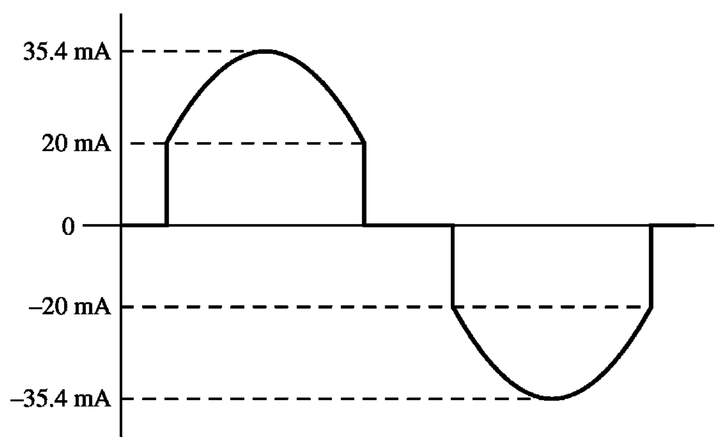

Figure 11-3

11. $I_p = \dfrac{15\text{ V}}{4.7\text{ k}\Omega} = 3.19\text{ mA}$

See Figure 11-4.

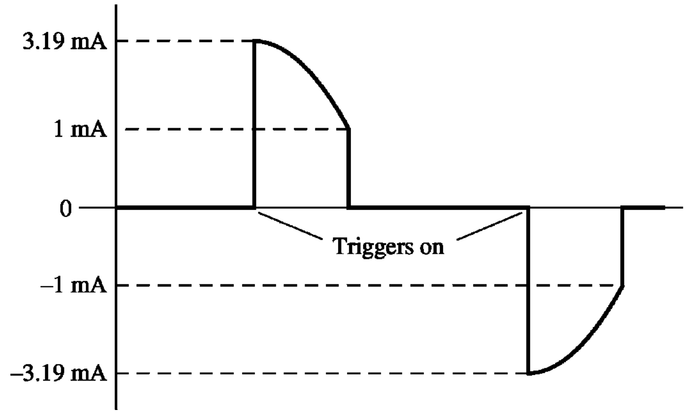

Figure 11-4

Section 11-5 The Silicon-Controlled Switch (SCS)

12. See Section 11-5 in the text.

13. Anode, cathode, anode gate, and cathode gate

Section 11-6 The (UJT)

14. $\eta = \dfrac{r'_{B1}}{r'_{B1} + r'_{B2}} = \dfrac{2.5\text{k}\Omega}{2.5\text{k}\Omega + 4\text{k}\Omega} = \mathbf{0.385}$

15. $V_p = \eta V_{\text{BB}} + V_{pn} = 0.385(15\text{ V}) + 0.7\text{ V} = \mathbf{6.48\text{ V}}$

16. $\dfrac{V_{\text{BB}} - V_v}{I_v} < R_1 < \dfrac{V_{\text{BB}} - V_P}{I_p}$

$\dfrac{12\text{ V} - 0.8\text{ V}}{15\text{ mA}} < R_1 < \dfrac{12\text{ V} - 10\text{ V}}{10\ \mu\text{A}}$

$\mathbf{747\ \Omega < R_1 < 200\text{ k}\Omega}$

Section 11-7 The Programmable Unijunction Transistor (PUT)

17. (a) $V_{\text{A}} = \left(\dfrac{R_3}{R_2 + R_3}\right)V_{\text{B}} + 0.7\text{ V} = \left(\dfrac{10\text{ k}\Omega}{22\text{ k}\Omega}\right)20\text{ V} + 0.7\text{ V} = \mathbf{9.79\text{ V}}$

(b) $V_{\text{A}} = \left(\dfrac{R_3}{R_2 + R_3}\right)V_{\text{B}} + 0.7\text{ V} = \left(\dfrac{47\text{ k}\Omega}{94\text{ k}\Omega}\right)9\text{ V} + 0.7\text{ V} = \mathbf{5.2\text{ V}}$

18. (a) From Problem 17(a), $V_A = 9.79\text{ V}$ at turn on.

$$I = \frac{9.79\text{ V}}{470\,\Omega} = 20.8\text{ mA} \text{ at turn on}$$

$$I_p = \frac{10\text{ V}}{470\,\Omega} = 21.3\text{ mA}$$

See Figure 11-5.

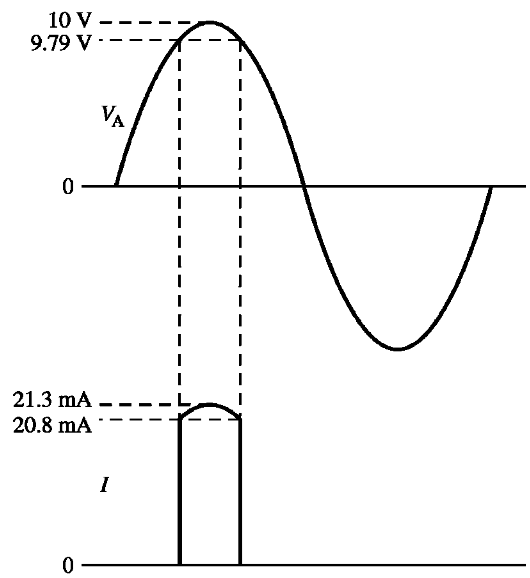

Figure 11-5

(b) From Problem 17(b), $V_A = 5.2\text{ V}$ at turn on.

$$I = \frac{5.2\text{ V}}{330\,\Omega} = 15.8\text{ mA at turn on}$$

$$I_p = \frac{10\text{ V}}{330\,\Omega} = 30.3\text{ mA}$$

See Figure 11-6.

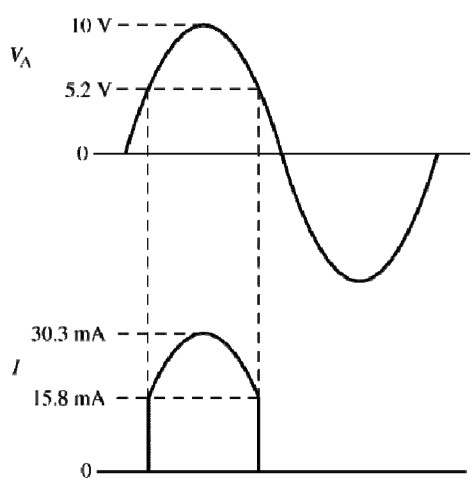

Figure 11-6

19. $$V_A = \left(\frac{R_3}{R_2 + R_3}\right)6\text{ V} + 0.7\text{ V} = \left(\frac{10\text{ k}\Omega}{20\text{ k}\Omega}\right)6\text{ V} + 0.7\text{ V} = 3.7\text{ V}\ \text{ at turn on}$$

$V_{R1} \cong V_A = 3.7\text{ V}$ at turn on.

See Figure 11-7.

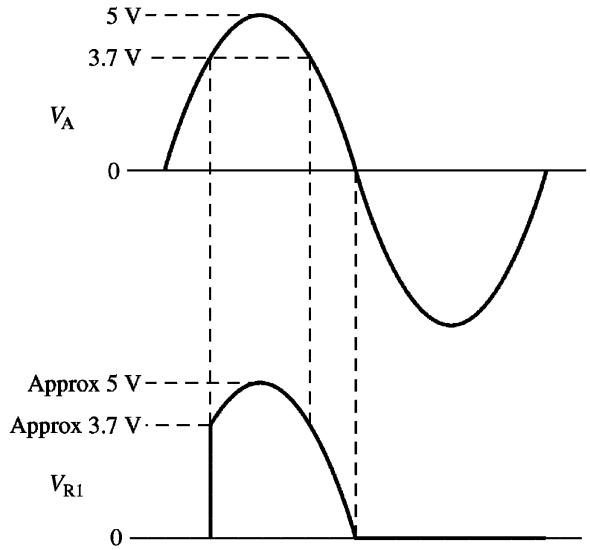

Figure 11-7

20. $$V_A = \left(\frac{15\text{ k}\Omega}{25\text{ k}\Omega}\right)6\text{ V} + 0.7\text{ V}$$

$= 4.3\text{ V}$ at turn on

$V_{R1} \cong V_A = 4.3\text{ V}$

See Figure 11-8.

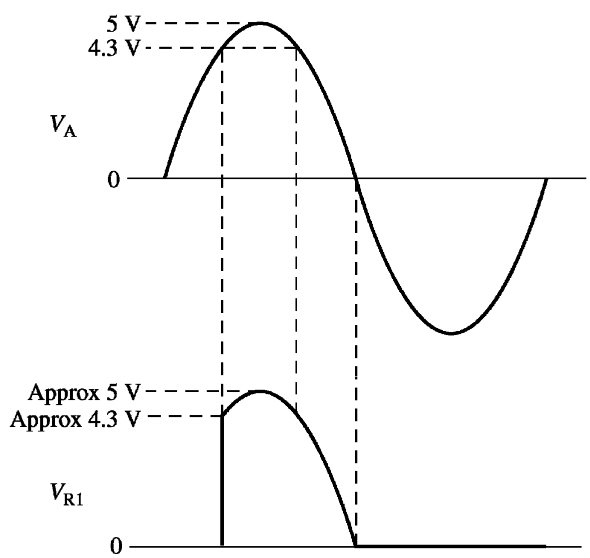

Figure 11-8

Device Application Problems

21. The motor runs fastest at **0 V** for the motor speed control circuit.

22. If the rheostat resistance decreases, the SCR turns on **earlier** in the ac cycle.

23. As the PUT gate voltage increases in the circuit, the PUT triggers on later in the ac cycle causing the SCR to fire later in the cycle, conduct for a shorter time, and decrease the power to the motor.

Advanced Problems

24. D_1: 15 V zener (1N4744)

R_1: 100 Ω, 1 W

R_2: 100 Ω, 1 W

Q_1: Any SCR with a 1 A minimum rating (1.5 A would be better)

R_3: 150 Ω, 1 W

25. See Figure 11-9.

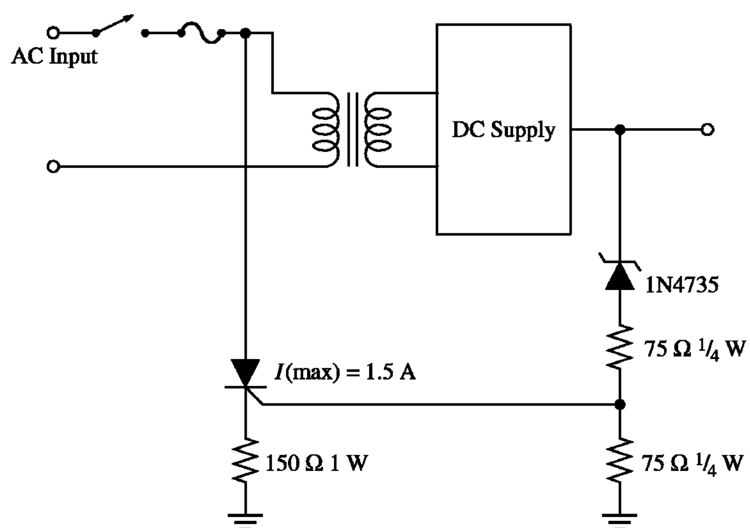

Figure 11-9

26. $V_p = \eta V_{\text{BB}} + V_{pn} = (0.75)(12\text{ V}) + 0.7\text{ V} = 9.7\text{ V}$

$I_v = 10\text{ mA}$ and $I_p = 20\ \mu\text{A}$

$$R_1 < \frac{12\text{ V} - 9.7\text{ V}}{20\mu\text{A}} = 115\text{ k}\Omega$$

$$R_1 > \frac{12\text{ V} - 1\text{ V}}{10\text{ mA}} = 1.1\text{ k}\Omega$$

Select $R_1 = 51\text{ k}\Omega$ as an intermediate value.

During the charging cycle:

$$V(t) = V_F - (V_F - V_0)e^{-t_1/R_1C}$$

$$9.7\text{ V} = 12\text{ V} - (12\text{ V} - 1\text{ V})e^{-t_1/R_1C}$$

$$-\frac{t_1}{R_1C} = \ln\left(\frac{2.3\text{ V}}{11\text{ V}}\right)$$

$$t_1 = -R_1C\ln\left(\frac{2.3\text{ V}}{11\text{ V}}\right) = 1.56R_1C = 79.8\times10^3C$$

During the discharging cycle (assuming $R_2 >> R_{B1}$):

$$V(t) = V_F - (V_F - V_0)e^{-t_2/R_2C}$$

$$1\text{ V} = 0\text{ V} - (0\text{ V} - 9.3\text{ V})e^{-t_2/R_2C}$$

$$-\frac{t_2}{R_2C} = \ln\left(\frac{1\text{ V}}{9.3\text{ V}}\right)$$

$$t_2 = -R_2C\ln\left(\frac{1\text{ V}}{9.3\text{ V}}\right) = 2.23R_2C$$

Let $R_2 = 100\text{ k}\Omega$, so $t_2 = 223\times10^3C$.

Since $f = 2.5\text{ kHz}$, $T = 400\,\mu\text{s}$

$$T = t_1 + t_2 = 79.8\times10^3C + 223\times10^3C = 303\times10^3C = 400\,\mu\text{s}$$

$$C = \frac{400\,\mu\text{s}}{303\times10^3} = 0.0013\,\mu\text{F}$$

See Figure 11-10.

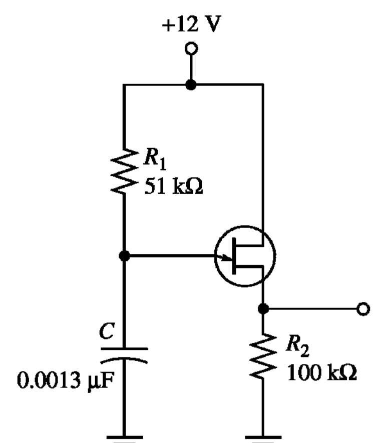

Figure 11-10

Multisim Troubleshooting Problems

27. Cathode-anode shorted

28. Gate-cathode open

29. R_1 shorted

Chapter 12
The Operational Amplifier

Section 12-1 Introduction to Operational Amplifiers

1. *Practical op-amp*: High open-loop gain, high input impedance. low output impedance, and high CMRR.

Ideal op-amp: Infinite open-loop gain, infinite input impedance, zero output impedance, and infinite CMRR.

2. Op amp 2 is more desirable because it has a higher input impedance, a lower output impedance, and a higher open-loop gain.

Section 12-2 Op-Amp Input Modes and Parameters

3. (a) Single-ended differential input

(b) Double-ended differential input

(c) Common-mode

4. CMRR (dB) = 20 log(250,000) = **108 dB**

5. $$\text{CMRR (dB)} = 20\log\left(\frac{A_{ol}}{A_{cm}}\right) = 20\log\left(\frac{175{,}000}{0.18}\right) = \mathbf{120\ dB}$$

6. $$\text{CMRR} = \frac{A_{ol}}{A_{cm}}$$

$$A_{cm} = \frac{A_{ol}}{\text{CMRR}} = \frac{90{,}000}{300{,}000} = \mathbf{0.3}$$

7. $$I_{\text{BIAS}} = \frac{8.3\ \mu\text{A} + 7.9\ \mu\text{A}}{2} = \mathbf{8.1\ \mu A}$$

8. Input bias current is the average of the two input currents. Input offset current is the difference between the two input currents.

$$I_{\text{OS}} = \left|8.3\ \mu\text{A} - 7.9\ \mu\text{A}\right| = \mathbf{400\ nA}$$

9. $$\text{Slew rate} = \frac{24\ \text{V}}{15\ \mu\text{s}} = \mathbf{1.6\ V/\mu s}$$

10. $\Delta t = \dfrac{\Delta V_{out}}{\text{slew rate}} = \dfrac{20\text{ V}}{0.5\text{ V}/\mu\text{s}} = \mathbf{40\ \mu s}$

Section 12-4 Op-Amps with Negative Feedback

11. (a) Voltage-follower

(b) Noninverting

(c) Inverting

12. $B = \dfrac{R_i}{R_i + R_f} = \dfrac{1.0\text{ k}\Omega}{101\text{ k}\Omega} = \mathbf{9.90 \times 10^{-3}}$

$V_f = BV_{out} = (9.90\times10^{-3})5\text{ V} = 0.0495\text{ V} = \mathbf{49.5\ mV}$

13. (a) $A_{cl(\text{NI})} = \dfrac{1}{B} = \dfrac{1}{1.5\text{ k}\Omega / 561.5\text{ k}\Omega} = \mathbf{374}$

(b) $V_{out} = A_{cl(\text{NI})}V_{in} = (374)(10\text{ mV}) = \mathbf{3.74\ V\ rms}$

(c) $V_f = \left(\dfrac{1.5\text{ k}\Omega}{561.5\text{ k}\Omega}\right)3.74\text{ V} = \mathbf{9.99\ mV\ rms}$

14. (a) $A_{cl(\text{NI})} = \dfrac{1}{B} = \dfrac{1}{4.7\text{ k}\Omega / 51.7\text{ k}\Omega} = \mathbf{11}$

(b) $A_{cl(\text{NI})} = \dfrac{1}{B} = \dfrac{1}{10\text{ k}\Omega / 1.01\text{ M}\Omega} = \mathbf{101}$

(c) $A_{cl(\text{NI})} = \dfrac{1}{B} = \dfrac{1}{4.7\text{ k}\Omega / 224.7\text{ k}\Omega} = \mathbf{47.8}$

(d) $A_{cl(\text{NI})} = \dfrac{1}{B} = \dfrac{1}{1.0\text{ k}\Omega / 23\text{ k}\Omega} = \mathbf{23}$

15. (a) $1 + \dfrac{R_f}{R_i} = A_{cl(\text{NI})}$

$R_f = R_i(A_{cl(\text{NI})} - 1) = 1.0\text{ k}\Omega(50-1) = \mathbf{49\ k\Omega}$

(b) $\dfrac{R_f}{R_i} = A_{cl(\text{I})}$

$R_f = -R_i(A_{cl(\text{I})}) = -10\text{ k}\Omega(-300) = \mathbf{3\ M\Omega}$

(c) $R_f = R_i(A_{cl(\text{NI})} - 1) = 12\text{ k}\Omega(7) = \mathbf{84\ k\Omega}$

(d) $R_f = -R_i(A_{cl(\text{I})}) = -2.2\text{ k}\Omega(-75) = \mathbf{165\ k\Omega}$

16. (a) $A_{cl(\text{VF})} = \mathbf{1}$

(b) $A_{cl(\text{I})} = -\left(\dfrac{R_f}{R_i}\right) = -\left(\dfrac{100\ \text{k}\Omega}{100\ \text{k}\Omega}\right) = \mathbf{-1}$

(c) $A_{cl(\text{NI})} = \dfrac{1}{\left(\dfrac{R_i}{R_i + R_f}\right)} = \dfrac{1}{\left(\dfrac{47\ \text{k}\Omega}{47\ \text{k}\Omega + 1.0\,\text{M}\Omega}\right)} = \mathbf{22}$

(d) $A_{cl(\text{I})} = -\left(\dfrac{R_f}{R_i}\right) = -\left(\dfrac{330\ \text{k}\Omega}{33\ \text{k}\Omega}\right) = \mathbf{-10}$

17. (a) $V_{out} \cong V_{in} = \mathbf{10\ mV,\ in\ phase}$

(b) $V_{out} = A_{cl}V_{in} = -\left(\dfrac{R_f}{R_i}\right)V_{in} = -(1)(10\ \text{mV}) = \mathbf{-10\ mV,\ 180°\ out\ of\ phase}$

(c) $V_{out} = V_{in} = \left(\dfrac{1}{\left(\frac{R_1}{R_i + R_f}\right)}\right)V_{in} = \left(\dfrac{1}{\left(\frac{47\ \text{k}\Omega}{1047\ \text{k}\Omega}\right)}\right)10\ \text{mV} = \mathbf{223\ mV,\ in\ phase}$

(d) $V_{out} = -\left(\dfrac{R_f}{R_i}\right)V_{in} = -\left(\dfrac{330\ \text{k}\Omega}{33\ \text{k}\Omega}\right)10\ \text{mV} = \mathbf{-100\ mV,\ 180°\ out\ of\ phase}$

18. (a) $I_{in} = \dfrac{V_{in}}{R_{in}} = \dfrac{1\ \text{V}}{2.2\ \text{k}\Omega} = \mathbf{455\ \boldsymbol{\mu}A}$

(b) $I_f \cong I_{in} = \mathbf{455\ \boldsymbol{\mu}A}$

(c) $V_{out} = -I_f R_f = -(455\ \mu\text{A})(22\ \text{k}\Omega) = \mathbf{-10\ V}$

(d) $A_{cl(\text{I})} = -\left(\dfrac{R_f}{R_i}\right) = -\left(\dfrac{22\ \text{k}\Omega}{2.2\ \text{k}\Omega}\right) = \mathbf{-10}$

Section 12-5 Effects of Negative Feedback on Op-Amp Impedances

19. (a) $B = \dfrac{2.7\ \text{k}\Omega}{562.5\ \text{k}\Omega} = 0.0048$

$$Z_{in(\text{NI})} = (1 + A_{ol})Z_{in} = [1 + (175{,}000)(0.0048)]10\ \text{M}\Omega = \mathbf{8.41\ G\Omega}$$

$$Z_{out(\text{NI})} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{75\ \Omega}{1 + (175{,}000)(0.0048)} = \mathbf{89.2\ m\Omega}$$

(b) $B = \dfrac{1.5\ \text{k}\Omega}{48.5\ \text{k}\Omega} = 0.031$

$Z_{in(\text{NI})} = (1 + A_{ol}B)Z_{in} = [1 + (200{,}000)(0.031)]1\ \text{M}\Omega = \mathbf{6.20\ G\Omega}$

$Z_{out(\text{NI})} = \dfrac{Z_{out}}{1 + A_{ol}B} = \dfrac{25\ \Omega}{1 + (200{,}000)(0.031)} = \mathbf{4.04\ m\Omega}$

(c) $B = \dfrac{56\ \text{k}\Omega}{1.056\ \text{M}\Omega} = 0.053$

$Z_{in(\text{NI})} = (1 + A_{ol}B)Z_{in} = [1 + (50{,}000)(0.053)]2\ \text{M}\Omega = \mathbf{5.30\ G\Omega}$

$Z_{out(\text{NI})} = \dfrac{Z_{out}}{1 + A_{ol}B} = \dfrac{50\ \Omega}{1 + (50{,}000)(0.053)} = \mathbf{19.0\ m\Omega}$

20. (a) $Z_{in(\text{VF})} = (1 + A_{ol})Z_{in} = (1 + 220{,}000)\,6\ \text{M}\Omega = 1.32 \times 10^{12}\,\Omega = \mathbf{1.32\ T\Omega}$

$Z_{out(\text{VF})} = \dfrac{Z_{out}}{1 + A_{ol}} = \dfrac{100\ \Omega}{1 + 220{,}000} = \mathbf{455\ \mu\Omega}$

(b) $Z_{in(\text{VF})} = (1 + A_{ol})Z_{in} = (1 + 100{,}000)\,5\ \text{M}\Omega = 5 \times 10^{11}\,\Omega = \mathbf{500\ G\Omega}$

$Z_{out(\text{VF})} = \dfrac{Z_{out}}{1 + A_{ol}} = \dfrac{60\ \Omega}{1 + 100{,}000} = \mathbf{600\ \mu\Omega}$

(c) $Z_{in(\text{VF})} = (1 + A_{ol})Z_{in} = (1 + 50{,}000)\,800\ \text{k}\Omega = \mathbf{40\ G\Omega}$

$Z_{out(\text{VF})} = \dfrac{Z_{out}}{1 + A_{ol}} = \dfrac{75\ \Omega}{1 + 500{,}000} = \mathbf{1.5\ m\Omega}$

21. (a) $Z_{in(\text{I})} \cong R_i = \mathbf{10\ k\Omega}$

$B = \dfrac{R_i}{R_i + R_f} = \dfrac{10\ \text{k}\Omega}{160\ \text{k}\Omega} = 0.0625$

$Z_{out(\text{I})} = \dfrac{Z_{out}}{1 + A_{ol}B} = \dfrac{40\ \Omega}{1 + (125{,}000)(0.0625)} = \mathbf{5.12\ m\Omega}$

(b) $Z_{in(\text{I})} \cong R_i = \mathbf{100\ k\Omega}$

$B = \dfrac{100\ \text{k}\Omega}{1.1\ \text{M}\Omega} = 0.091$

$Z_{out(\text{I})} = \dfrac{Z_{out}}{1 + A_{ol}B} = \dfrac{50\ \Omega}{1 + (75{,}000)(0.091)} = \mathbf{7.32\ m\Omega}$

(c) $Z_{in(\mathrm{I})} \cong R_i = \mathbf{470\ k\Omega}$

$$B = \frac{470\ \Omega}{10{,}470\ \Omega} = 0.045$$

$$Z_{out(\mathrm{I})} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{70\ \Omega}{1 + (250{,}000)(0.045)} = \mathbf{6.22\ m\Omega}$$

Section 12-6 Bias Current and Offset Voltage

22. (a) $R_{comp} = R_{in} = \mathbf{75\ \Omega}$ placed in the feedback path.

$I_{\mathrm{OS}} = |42\ \mu\mathrm{A} - 40\ \mu\mathrm{A}| = 2\ \mu\mathrm{A}$

(b) $V_{\mathrm{OUT(error)}} = A_v I_{\mathrm{OS}} R_{in} = (1)(2\ \mu\mathrm{A})(75\ \Omega) = \mathbf{150\ \mu V}$

23. (a) $R_c = R_i \parallel R_f = 2.7\ \mathrm{k\Omega} \parallel 560\ \mathrm{k\Omega} = \mathbf{2.69\ k\Omega}$

(b) $R_c = R_i \parallel R_f = 1.5\ \mathrm{k\Omega} \parallel 47\ \mathrm{k\Omega} = \mathbf{1.45\ k\Omega}$

(c) $R_c = R_i \parallel R_f = 56\ \mathrm{k\Omega} \parallel 1.0\ \mathrm{M\Omega} = \mathbf{53\ k\Omega}$

See Figure 12-1.

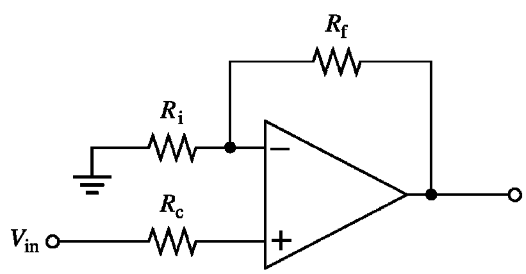

Figure 12-1

24. $V_{\mathrm{OUT(error)}} = A_v V_{\mathrm{IO}} = (1)(2\ \mathrm{nV}) = \mathbf{2\ nV}$

25. $V_{\mathrm{OUT(error)}} = (1 + A_{ol})V_{\mathrm{IO}}$

$$V_{\mathrm{IO}} = \frac{V_{\mathrm{OUT(error)}}}{A_{ol}} = \frac{35\ \mathrm{mV}}{200{,}000} = \mathbf{175\ nV}$$

Section 12-7 Open-Loop Frequency and Phase Responses

26. $A_{cl} = 120\text{ dB} - 50\text{ dB} = \mathbf{70\ dB}$

27. The gain is ideally **175,000** at 200 Hz. The midrange dB gain is

20 log(175,000) = 105 dB

The actual gain at 200 Hz is

$$A_{v(\text{dB})} = 105\text{ dB} - 3\text{ dB} = 102\text{ dB}$$

$$A_v = \log^{-1}\left(\frac{102}{20}\right) = \mathbf{125{,}892}$$

$$BW_{ol} = \mathbf{200\ Hz}$$

28. $$\frac{f_c}{f} = \frac{X_C}{R}$$

$$X_C = \frac{Rf_c}{f} = \frac{(1.0\text{ k}\Omega)(5\text{ kHz})}{3\text{ kHz}} = \mathbf{1.67\ k\Omega}$$

29. (a) $$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}} = \frac{1}{\sqrt{1+\left(\frac{1\text{ kHz}}{12\text{ kHz}}\right)^2}} = \mathbf{0.997}$$

(b) $$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}} = \frac{1}{\sqrt{1+\left(\frac{5\text{ kHz}}{12\text{ kHz}}\right)^2}} = \mathbf{0.923}$$

(c) $$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}} = \frac{1}{\sqrt{1+\left(\frac{12\text{ kHz}}{12\text{ kHz}}\right)^2}} = \mathbf{0.707}$$

(d) $$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}} = \frac{1}{\sqrt{1+\left(\frac{20\text{ kHz}}{12\text{ kHz}}\right)^2}} = \mathbf{0.515}$$

(e) $$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}} = \frac{1}{\sqrt{1+\left(\frac{100\text{ kHz}}{12\text{ kHz}}\right)^2}} = \mathbf{0.119}$$

30. (a) $$A_{ol} = \frac{A_{ol(mid)}}{\sqrt{1+\left(\frac{f}{f_{c(ol)}}\right)^2}} = \frac{80{,}000}{\sqrt{1+\left(\frac{100\text{ kHz}}{1\text{ kHz}}\right)^2}} = \mathbf{79{,}603}$$

(b) $$A_{ol} = \frac{A_{ol(mid)}}{\sqrt{1+\left(\frac{f}{f_{c(ol)}}\right)^2}} = \frac{80{,}000}{\sqrt{1+\left(\frac{1\text{ kHz}}{1\text{ kHz}}\right)^2}} = \mathbf{56{,}569}$$

(c) $$A_{ol} = \frac{A_{ol(mid)}}{\sqrt{1+\left(\frac{f}{f_{c(ol)}}\right)^2}} = \frac{80{,}000}{\sqrt{1+\left(\frac{10\text{ kHz}}{1\text{ kHz}}\right)^2}} = \mathbf{7960}$$

(d) $$A_{ol} = \frac{A_{ol(mid)}}{\sqrt{1+\left(\frac{f}{f_{c(ol)}}\right)^2}} = \frac{80{,}000}{\sqrt{1+\left(\frac{1\text{ MHz}}{1\text{ kHz}}\right)^2}} = \mathbf{80}$$

31. (a) $$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi(10\text{ k}\Omega)(0.01\ \mu\text{F})} = 1.59\text{ kHz};\ \theta = \tan^{-1}\left(\frac{f}{f_c}\right) = \tan^{-1}\left(\frac{2\text{ kHz}}{1.59\text{ kHz}}\right) = \mathbf{-51.5^\circ}$$

(b) $$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi(1.0\text{ k}\Omega)(0.01\ \mu\text{F})} = 15.9\text{ kHz};\ \theta = \tan^{-1}\left(\frac{f}{f_c}\right) = \tan^{-1}\left(\frac{2\text{ kHz}}{15.9\text{ kHz}}\right) = \mathbf{-7.17^\circ}$$

(c) $$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi(100\text{ k}\Omega)(0.01\ \mu\text{F})} = 159\text{ Hz};\ \theta = \tan^{-1}\left(\frac{f}{f_c}\right) = \tan^{-1}\left(\frac{2\text{ kHz}}{159\text{ kHz}}\right) = \mathbf{-85.5^\circ}$$

32. (a) $$\theta = \tan^{-1}\left(\frac{f}{f_c}\right) = \tan^{-1}\left(\frac{100\text{ Hz}}{8.5\text{ kHz}}\right) = \mathbf{-0.674^\circ}$$

(b) $$\theta = \tan^{-1}\left(\frac{f}{f_c}\right) = \tan^{-1}\left(\frac{400\text{ Hz}}{8.5\text{ kHz}}\right) = \mathbf{-2.69^\circ}$$

(c) $$\theta = \tan^{-1}\left(\frac{f}{f_c}\right) = \tan^{-1}\left(\frac{850\text{ Hz}}{8.5\text{ kHz}}\right) = \mathbf{-5.71^\circ}$$

(d) $$\theta = \tan^{-1}\left(\frac{f}{f_c}\right) = \tan^{-1}\left(\frac{8.5\text{ kHz}}{8.5\text{ kHz}}\right) = \mathbf{-45.0^\circ}$$

(e) $$\theta = \tan^{-1}\left(\frac{f}{f_c}\right) = \tan^{-1}\left(\frac{25\text{ kHz}}{8.5\text{ kHz}}\right) = \mathbf{-71.2^\circ}$$

(f) $$\theta = \tan^{-1}\left(\frac{f}{f_c}\right) = \tan^{-1}\left(\frac{85\text{ kHz}}{8.5\text{ kHz}}\right) = \mathbf{-84.3^\circ}$$

See Figure 12-2.

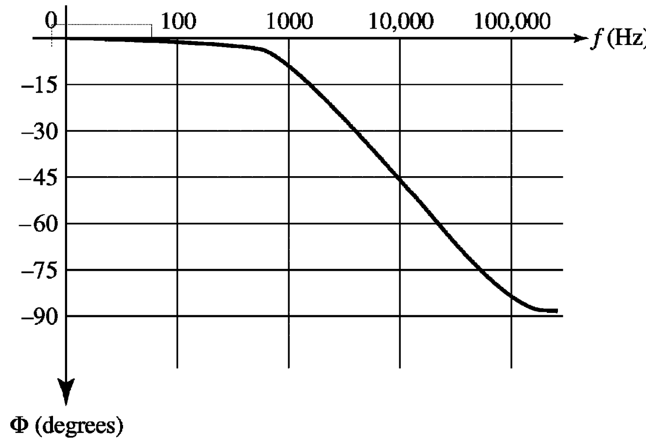

Figure 12-2

33. (a) $A_{ol(mid)} = 30\text{ dB} + 40\text{ dB} + 20\text{ dB} = \mathbf{90\ dB}$

(b) $\theta_1 = -\tan^{-1}\left(\frac{f}{f_c}\right) = -\tan^{-1}\left(\frac{10\text{ kHz}}{600\text{ Hz}}\right) = -86.6°$

$\theta_2 = -\tan^{-1}\left(\frac{f}{f_c}\right) = -\tan^{-1}\left(\frac{10\text{ kHz}}{50\text{ kHz}}\right) = -11.3°$

$\theta_3 = -\tan^{-1}\left(\frac{f}{f_c}\right) = -\tan^{-1}\left(\frac{10\text{ kHz}}{200\text{ kHz}}\right) = -2.86°$

$\theta_{tot} = -86.6° - 11.3° - 2.86° - 180° = \mathbf{-281°}$

34. (a) 0 dB/decade

(b) –20 dB/decade

(c) –40 dB/decade

(d) –60 dB/decade

Section 12-8 Closed-Loop Frequency Response

35. (a) $A_{cl(\text{I})} = -\left(\frac{R_f}{R_i}\right) = -\left(\frac{68\text{ k}\Omega}{2.2\text{ k}\Omega}\right) = -30.9$; $A_{cl(\text{I})}(\text{dB}) = 20\log(30.9) = \mathbf{29.8\ dB}$

(b) $A_{cl(\text{NI})} = \frac{1}{B} = \frac{1}{15\text{ k}\Omega / 235\text{ k}\Omega} = 15.7$; $A_{cl(\text{NI})}(\text{dB}) = 20\log(15.7) = \mathbf{23.9\ dB}$

(c) $A_{cl(\text{VF})} = 1$; $A_{cl(\text{VF})}(\text{dB}) = 20\log(1) = \mathbf{0\ dB}$

These are all closed-loop gains.

36. $BW_{cl} = BW_{ol}(1 + BA_{ol(mid)}) = 1500\text{ Hz}[1 + (0.015)(180{,}000)] = \mathbf{4.05\ MHz}$

37. $A_{ol}(\text{dB}) = 89\text{ dB}$

$A_{ol} = 28{,}184$

$A_{cl}f_{c(cl)} = A_{ol}f_{c(ol)}$

$$A_{cl} = \frac{A_{ol}f_{c(ol)}}{f_{c(cl)}} = \frac{(28{,}184)(750\text{ Hz})}{5.5\text{ kHz}} = 3843$$

$A_{cl}(\text{dB}) = 20\log(3843) = \mathbf{71.7\ dB}$

38. $$A_{cl} = \frac{A_{ol}f_{c(ol)}}{f_{c(cl)}} = \frac{(28{,}184)(750\text{ Hz})}{5.5\text{ kHz}} = 3843$$

$f_T = A_{cl}f_{c(cl)} = (3843)(5.5\text{ kHz}) = \mathbf{21.1\ MHz}$

39. (a) $A_{cl(\text{VF})} = \mathbf{1}$

$$BW = f_{c(cl)} = \frac{f_T}{A_{cl}} = \frac{28\text{ MHz}}{1} = \mathbf{2.8\ MHz}$$

(b) $$A_{cl(\text{I})} = -\frac{100\text{ k}\Omega}{2.2\text{ k}\Omega} = \mathbf{-45.5}$$

$$BW = \frac{2.8\text{ MHz}}{45.5} = \mathbf{61.6\ kHz}$$

(c) $$A_{cl(\text{NI})} = 1 + \frac{12\text{ k}\Omega}{1.0\text{ k}\Omega} = \mathbf{13}$$

$$BW = \frac{2.8\text{ MHz}}{13} = \mathbf{215\ kHz}$$

(d) $$A_{cl(\text{I})} = -\frac{1\text{ M}\Omega}{5.6\text{ k}\Omega} = \mathbf{-179}$$

$$BW = \frac{2.8\text{ MHz}}{179} = \mathbf{15.7\ kHz}$$

40. (a) $$A_{cl} = \frac{150\text{ k}\Omega}{22\text{ k}\Omega} = 6.8$$

$$f_{c(cl)} = \frac{A_{ol}f_{c(ol)}}{A_{cl}} = \frac{(120{,}000)(150\text{ Hz})}{6.8} = 2.65\text{ MHz}$$

$BW = f_{c(cl)} = \mathbf{2.65\ MHz}$

(b) $A_{cl} = \dfrac{1.0\text{ M}\Omega}{10\text{ k}\Omega} = 100$

$$f_{c(cl)} = \frac{A_{ol} f_{c(ol)}}{A_{cl}} = \frac{(195{,}000)(50\text{ Hz})}{100} = 97.5\text{ kHz}$$

$$BW = f_{c(cl)} = \mathbf{97.5\ kHz}$$

Section 12-9 Troubleshooting

41. (a) Faulty op-amp or open R_1

(b) R_2 open, forcing open-loop operation

42. (a) Circuit becomes a voltage-follower and the output replicates the input.

(b) Output will saturate.

(c) No effect on the ac; may add or subtract a small dc voltage to the output.

(d) The voltage gain will change from 10 to 0.1.

43. The gain becomes a fixed –100 with no effect as the potentiometer is adjusted.

Device Application Problems

44. The push-pull stage will operate nonlinearly if a diode is shorted, a transistor is faulty, or the op-amp stage has excessive gain.

45. If a 100 kΩ resistor is used for R_2, the gain of the op amp will be reduced by a factor of 100.

46. If D_1 opens, the positive half of the signal will appear on the output through Q_3 and Q_4. The negative half is missing due to the open diode.

Datasheet Problems

47. From the datasheet of textbook Figure 12-78:

$$B = \frac{470\ \Omega}{47\text{ k}\Omega + 470\ \Omega} = 0.0099$$

$$A_{ol} = 200{,}000 \ \text{(typical)}$$

$$Z_{in} = 2.0\text{ M}\Omega \ \text{(typical)}$$

$$Z_{in(\text{NI})} = (1 + 0.0099)(200{,}000)(2\text{ M}\Omega) = (1 + 1980)2\text{ M}\Omega = \mathbf{3.96\ G\Omega}$$

48. From the datasheet in textbook Figure 12-78:

$$Z_{in(\mathrm{I})} = R_i = \frac{R_f}{A_{cl}} = \frac{100\ \mathrm{k\Omega}}{100} = \mathbf{1\ k\Omega}$$

49. $$A_{ol} = 50\ \mathrm{V/mV} = \frac{50\ \mathrm{V}}{1\ \mathrm{mV}} = \frac{50{,}000\ \mathrm{V}}{1\ \mathrm{V}} = \mathbf{50{,}000}$$

50. Slew rate $= 0.5\ \mathrm{V}/\mu\mathrm{s}$

$$\Delta V = 8\ \mathrm{V} - (-8\ \mathrm{V}) = 16\ \mathrm{V}$$

$$\Delta t = \frac{16\ \mathrm{V}}{0.5\ \mathrm{V}/\mu\mathrm{s}} = \mathbf{32\ \mu s}$$

Advanced Problems

51. Using available standard values of $R_f = 150\ \mathrm{k\Omega}$ and $R_i = 1.0\ \mathrm{k\Omega}$,

$$A_v = 1 + \frac{150\ \mathrm{k\Omega}}{1.0\ \mathrm{k\Omega}} = 151$$

$$B = \frac{1.0\ \mathrm{k\Omega}}{151\ \mathrm{k\Omega}} = 6.62\times 10^{-3}$$

$$Z_{in(\mathrm{NI})} = (1 + (6.62\times 10^{-3})(50{,}000))300\ \mathrm{k\Omega} = 99.6\ \mathrm{M\Omega}$$

The compensating resistor is

$$R_c = R_i \parallel R_f = 150\ \mathrm{k\Omega} \parallel 1.0\ \mathrm{k\Omega} = 993\ \Omega$$

See Figure 12-3.

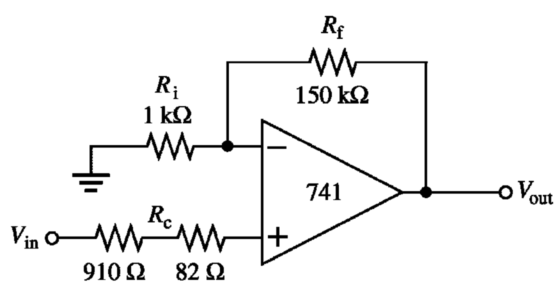

Figure 12-3

52. See Figure 12-4. 2% tolerance resistors are used to achieve a 5% gain tolerance.

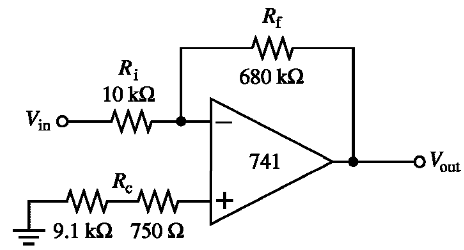

Figure 12-4

53. From textbook Figure 12-79:

$f_c = 10$ kHz at $A_v = 40$ dB $= 100$

In this circuit

$$A_v = 1 + \frac{33\text{ k}\Omega}{333\ \Omega} = 100.1 \cong 100$$

The compensating resistor is

$R_c = 33\text{ k}\Omega \parallel 333\ \Omega = 330\ \Omega$

See Figure 12-5.

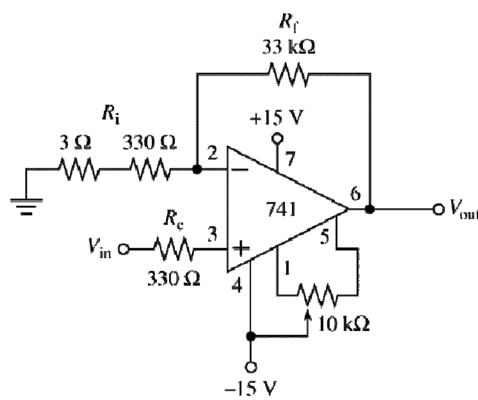

Figure 12-5

54. From textbook Figure 12-80:

For a ±10 V output swing minimum, the load must be 600 Ω for a ±10 V and ≈ 620 Ω for −10 V. So, the minimum load is **620 Ω**.

55. For the amplifier,

$$A_v = -\frac{100\ \text{k}\Omega}{2\ \text{k}\Omega} = -50$$

The compensating resistor is

$$R_c = 100\ \text{k}\Omega \parallel 2\ \text{k}\Omega = 1.96\ \text{k}\Omega \cong 2\ \text{k}\Omega$$

See Figure 12-6.

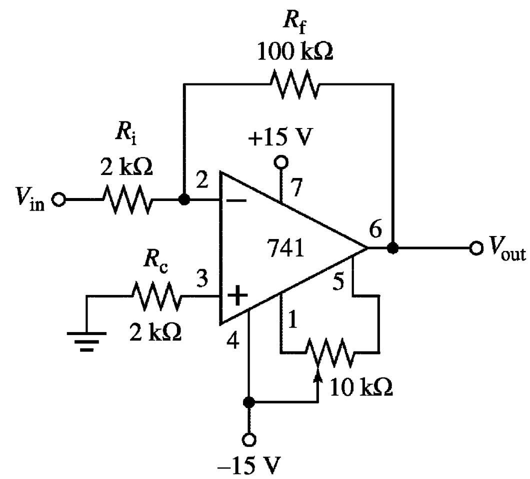

Figure 12-6

56. From textbook Figure 12-79 the maximum 741 closed loop gain with BW = 5 kHz is approximately 60 dB – (20 dB)log(5 kHz/1 kHz) = 60 dB – (20 dB)(0.7) = **46 dB**

$$A_{v(\text{dB})} = 20 \log A_v$$

$$A_v = \log^{-1}\left(\frac{A_{v(\text{dB})}}{20}\right) = \log^{-1}\left(\frac{46}{20}\right) = \mathbf{200}$$

Multisim Troubleshooting Problems

57. R_f open

58. R_i open

59. R_f leaky

60. R_i shorted

61. R_f shorted

62. Op-amp input to output open

63. R_f leaky

Chapter 12

64. R_i leaky

65. R_i shorted

66. R_i open

67. R_f open

68. R_f leaky

69. R_f open

70. R_f shorted

71. R_i open

72. R_i leaky

Chapter 13
Basic Op-Amp Circuits

Section 13-1 Comparators

1. $V_{out(p)} = A_{ol}V_{in} = (80{,}000)(0.15\text{ mV})(1.414) = 17\text{ V}$

Since 12 V is the peak limit, the op-amp saturates.

$V_{out(pp)} = \mathbf{24V}$ **with distortion due to clipping.**

2. (a) Maximum negative

(b) Maximum positive

(c) Maximum negative

3. $$V_{\text{UTP}} = \left(\frac{R_2}{R_1 + R_2}\right)(+10\text{ V}) = \left(\frac{18\text{ k}\Omega}{65\text{ k}\Omega}\right)10\text{ V} = \mathbf{2.77\text{ V}}$$

$$V_{\text{LTP}} = \left(\frac{R_2}{R_1 + R_2}\right)(-10\text{ V}) = \left(\frac{18\text{ k}\Omega}{65\text{ k}\Omega}\right)(-10\text{ V}) = \mathbf{-2.77\text{ V}}$$

4. $V_{\text{HYS}} = V_{\text{UTP}} - V_{\text{LTP}} = 2.77\text{ V} - (-2.77\text{ V}) = \mathbf{5.54\text{ V}}$

5. See Figure 13-1.

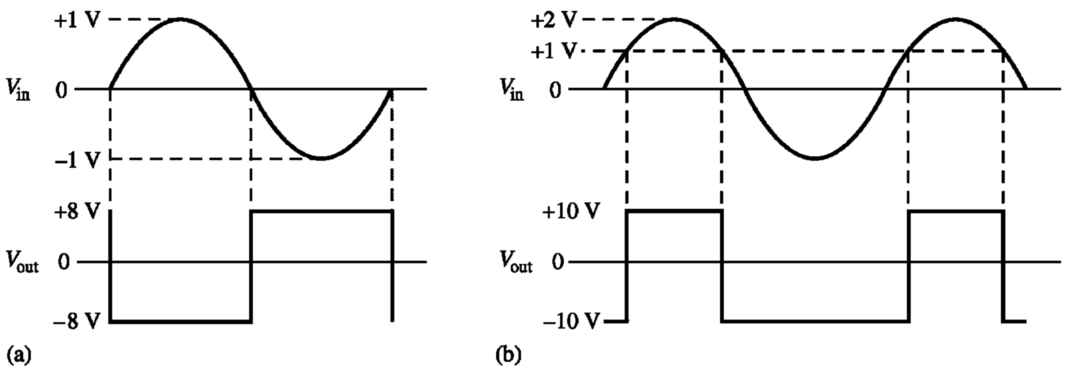

Figure 13-1

Chapter 13

6. (a) $$V_{\text{UTP}} = \left(\frac{R_2}{R_1 + R_2}\right)\left(+V_{out(max)}\right)\left(\frac{18\ \text{k}\Omega}{51\ \text{k}\Omega}\right)11\ \text{V} = 3.88\ \text{V}$$

$$V_{\text{LTP}} = -3.88\ \text{V}$$

$$V_{\text{HYS}} = V_{\text{UTP}} - V_{\text{LTP}} = 3.88\ \text{V} - (-3.88\ \text{V}) = \mathbf{7.76\ V}$$

(b) $$V_{\text{UTP}} = \left(\frac{R_2}{R_1 + R_2}\right)\left(+V_{out(max)}\right) = \left(\frac{68\ \text{k}\Omega}{218\ \text{k}\Omega}\right)11\ \text{V} = 3.43\ \text{V}$$

$$V_{\text{LTP}} = -3.43\ \text{V}$$

$$V_{\text{HYS}} = V_{\text{UTP}} - V_{\text{LTP}} = 3.43\ \text{V} - (-3.43\ \text{V}) = \mathbf{6.86\ V}$$

7. When the zener is forward-biased:

$$V_{out} = \left(\frac{18\ \text{k}\Omega}{18\ \text{k}\Omega + 47\ \text{k}\Omega}\right)V_{out} - 0.7\ \text{V}$$

$$V_{out} = (0.277)V_{out} - 0.7\ \text{V}$$

$$V_{out}(1 - 0.277) = -0.7\ \text{V}$$

$$V_{out} = \frac{-0.7\ \text{V}}{1 - 0.277} = \mathbf{-0.968\ V}$$

When the zener is reverse-biased:

$$V_{out} = \left(\frac{18\ \text{k}\Omega}{18\ \text{k}\Omega + 47\ \text{k}\Omega}\right)V_{out} + 6.2\ \text{V}$$

$$V_{out} = (0.277)V_{out} + 6.2\ \text{V}$$

$$V_{out}(1 - 0.277) = +6.2\ \text{V}$$

$$V_{out} = \frac{+6.2\ \text{V}}{1 - 0.277} = \mathbf{+8.57\ V}$$

8. $$V_{out} = \left(\frac{10\ \text{k}\Omega}{10\ \text{k}\Omega + 47\ \text{k}\Omega}\right)V_{out} \pm (4.7\ \text{V} + 0.7\ \text{V})$$

$$V_{out} = (0.175)V_{out} \pm 5.4\ \text{V}$$

$$V_{out} = \frac{\pm 5.4\ \text{V}}{1 - 0.175} = \pm 6.55\ \text{V}$$

$$V_{\text{UTP}} = (0.175)(+6.55\ \text{V}) = +1.15\ \text{V}$$

$$V_{\text{LTP}} = (0.175)(-6.55\ \text{V}) = -1.15\ \text{V}$$

See Figure 13-2.

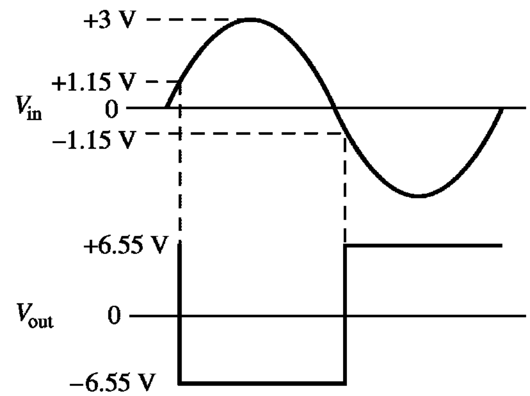

Figure 13-2

Section 13-2 Summing Amplifiers

9. (a) $V_{\text{OUT}} = -\dfrac{R_f}{R_i}(+1\text{ V} + 1.5\text{ V}) = -1(1\text{ V} + 1.5\text{ V}) = \mathbf{-2.5\ V}$

(b) $V_{\text{OUT}} = -\dfrac{R_f}{R_i}(0.1\text{ V} + 1\text{ V} + 0.5\text{ V}) = -\dfrac{22\text{ k}\Omega}{10\text{ k}\Omega}(1.6\text{ V}) = \mathbf{-3.52\ V}$

10. (a) $V_{\text{R1}} = \mathbf{1\ V}$

$V_{\text{R2}} = \mathbf{1.8\ V}$

(b) $I_{\text{R1}} = \dfrac{1\text{ V}}{22\text{ k}\Omega} = 45.5\ \mu\text{A}$

$I_{\text{R2}} = \dfrac{1.8\text{ V}}{22\text{ k}\Omega} = 81.8\ \mu\text{A}$

$I_f = I_{\text{R1}} + I_{\text{R2}} = 45.5\ \mu\text{A} + 81.8\ \mu\text{A} = \mathbf{127\ \mu A}$

(c) $V_{\text{OUT}} = -I_f R_f = -(127\ \mu\text{A})(22\text{ k}\Omega) = \mathbf{-2.8\ V}$

11. $5V_{in} = \left(\dfrac{R_f}{R}\right)V_{in}$

$\dfrac{R_f}{R} = 5$

$R_f = 5R = 5(22\text{ k}\Omega) = \mathbf{110\ k\Omega}$

12. See Figure 13-3.

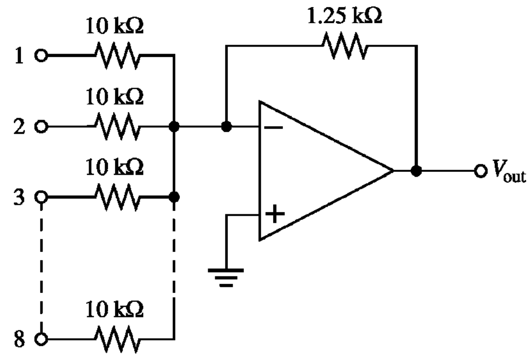

Figure 13-3

13. $$V_{\text{OUT}} = -\left[\left(\frac{R_f}{R_1}\right)V_1 + \left(\frac{R_f}{R_2}\right)V_2 + \left(\frac{R_f}{R_3}\right)V_3 + \left(\frac{R_f}{R_4}\right)V_4\right]$$

$$= -\left[\left(\frac{10\text{ k}\Omega}{10\text{ k}\Omega}\right)2\text{ V} + \left(\frac{10\text{ k}\Omega}{33\text{ k}\Omega}\right)3\text{ V} + \left(\frac{10\text{ k}\Omega}{91\text{ k}\Omega}\right)3\text{ V} + \left(\frac{10\text{ k}\Omega}{180\text{ k}\Omega}\right)6\text{ V}\right]$$

$$= -(2\text{ V} + 0.91\text{ V} + 0.33\text{ V} + 0.33\text{ V}) = \mathbf{-3.57\text{ V}}$$

$$I_f = \frac{V_{\text{out}}}{R_f} = \frac{3.57\text{ V}}{10\text{ k}\Omega} = \mathbf{357\ \mu A}$$

14. $R_f = \mathbf{100\text{ k}\Omega}$

Input resistors: $R_1 = \mathbf{100\text{ k}\Omega}$, $R_2 = \mathbf{50\text{ k}\Omega}$, $R_3 = \mathbf{25\text{ k}\Omega}$, $R_4 = \mathbf{12.5\text{ k}\Omega}$, $R_5 = \mathbf{6.25\text{ k}\Omega}$, $R_6 = \mathbf{3.125\text{ k}\Omega}$

Section 13-3 Integrators and Differentiators

15. $$\frac{dV_{out}}{dt} = -\frac{V_{\text{IN}}}{RC} = -\frac{5\text{ V}}{(56\text{ k}\Omega)(0.022\ \mu\text{F})} = \mathbf{-4.06\text{ mV}/\mu s}$$

16. See Figure 13-4.

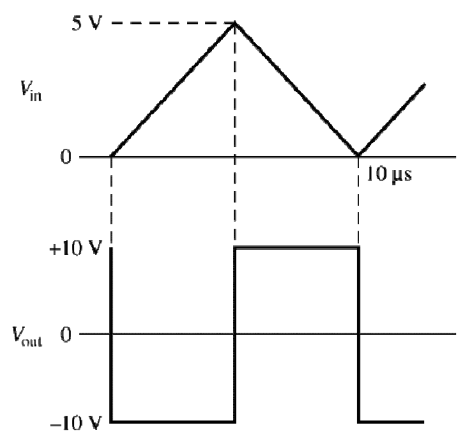

Figure 13-4

17. $I = \dfrac{CV_{pp}}{T/2} = \dfrac{(0.001\ \mu\text{F})(5\ \text{V})}{10\ \mu s/2} = \mathbf{1\ mA}$

18. $V_{out} = \pm RC\left(\dfrac{V_{pp}}{T/2}\right) = \pm(15\ \text{k}\Omega)(0.047\ \mu\text{F})\left(\dfrac{2\ \text{V}}{0.5\ \text{ms}}\right) = \mathbf{\pm 2.82\ V}$

See Figure 13-5.

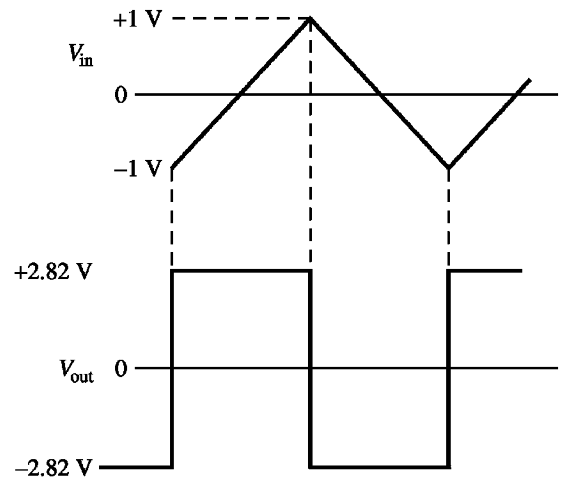

Figure 13-5

19. For the 10 ms interval when the switch is in position 2:

$$\frac{\Delta V_{out}}{\Delta t} = -\frac{V_{IN}}{RC} = -\frac{5\ \text{V}}{(10\ \text{k}\Omega)(10\ \mu\text{F})} = -\frac{5\ \text{V}}{0.1\ \text{s}} = -50\ \text{V/s} = -50\ \text{mV/ms}$$

$$\Delta V_{out} = (-50\ \text{mV/ms})(10\ \text{ms}) = -500\ \text{mV} = -0.5\ \text{V}$$

For the 10 ms interval when the switch is in position 1:

$$\frac{\Delta V_{out}}{\Delta t} = -\frac{V_{IN}}{RC} = -\frac{-5\ \text{V}}{(10\ \text{k}\Omega)(10\ \mu\text{F})} = -\frac{-5\ \text{V}}{0.1\ \text{s}} = +50\ \text{V/s} = +50\ \text{mV/ms}$$

$$\Delta V_{out} = (+50\ \text{mV/ms})(10\ \text{ms}) = +500\ \text{mV} = +0.5\ \text{V}$$

See Figure 13-6

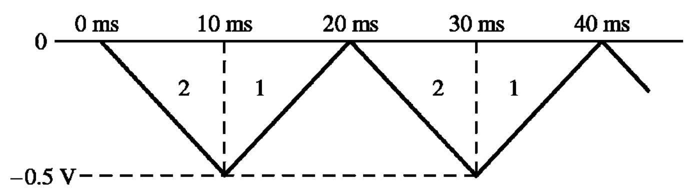

Figure 13-6

Section 13-4 Troubleshooting

20. $V_B = \left(\dfrac{R_2}{R_1 + R_2}\right)V_{out} \pm (V_Z + 0.7\text{ V})$

$$V_B = \frac{\pm(V_Z + 0.7\text{ V})}{1 - \left(\dfrac{R_2}{R_1 + R_2}\right)}$$

Normally, V_B should be

$$V_B = \frac{\pm(4.3\text{ V} + 0.7\text{ V})}{1 - 0.5} = \pm 10\text{ V}$$

Since the negative portion of V_B is only –1.4 V, zener ***D*₂ must be shorted**:

$$V_B = \frac{-(0\text{ V} + 0.7\text{ V})}{1 - 0.5} = 1.4\text{ V}$$

21. The output should be as shown in Figure 13-7. V_2 has no effect on the output. This indicates that ***R*₂ is open**.

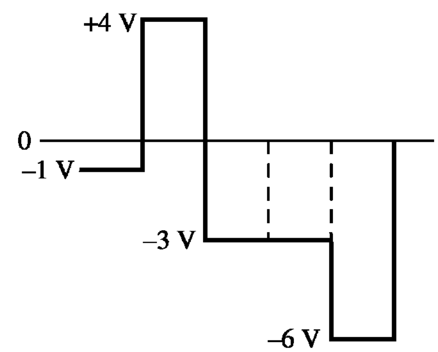

Figure 13-7

22. $V_v = \dfrac{2.5\text{ k}\Omega}{10\text{ k}\Omega} = 0.25$

The output should be as shown in Figure 13-8. An **open *R*₂** (V_2 is missing) will produce the observed output, which is incorrect.

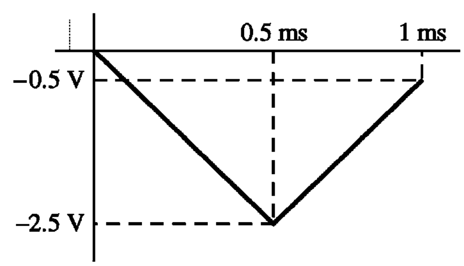

Figure 13-8

23. The D_2 input is missing (acts as a constant 0). This indicates an **open 50 kΩ resistor**.

Device Application Problems

24. The first thing that you should always do is visually inspect the circuit for bad contacts or loose connections, shorts from solder splashes or wire clippings, incorrect components, and incorrectly installed components. After careful inspection, you have found nothing wrong. Measurements are now necessary to isolate a component's fault.

25. An open decoupling capacitor can make the circuit more susceptible to power line noise.

26. If a 1.0 kΩ resistor is used for R_1, the inverting input would be increased, causing the pulse width to narrow for a given setting of the potentiometer.

Advanced Problems

27. $I_{\text{R1-2-3}} = \dfrac{24\text{ V}}{612\text{ k}\Omega} = 39.2\ \mu\text{A}$

Minimum setting of R_2:

$V_{\text{INV}} = 12\text{ V} - (39.2\ \mu\text{A})(56\text{ k}\Omega) = 9.8\text{ V}$

$v = V_p \sin\theta$

$\sin\theta = \dfrac{v}{V_p} = \dfrac{9.8\text{ V}}{10\text{ V}} = 0.98$

$\theta = \sin^{-1}\left(\dfrac{v}{V_p}\right) = \sin^{-1}(0.98) = 78.5°$ (on positive half cycle)

Angle from 78.5° to 90°

$\Delta\theta = 90° - 78.5° = 11.5°$

Angle from 90° to next point at which $v = 9.8$ V:

$\Delta\theta = 11.5°$

Angle from first point at which $v = 9.8$ V to second point at which $v = 9.8$ V on sine wave is

$\theta = 11.5° + 11.5° = 23°$

min. duty cycle $= \left(\dfrac{23°}{360°}\right)100 = \mathbf{6.39\%}$

See Figure 13-9(a).

Maximum setting of R_2:

$V_{\text{INV}} = 12\text{ V} - (39.2\ \mu\text{A})(556\text{ k}\Omega) = -9.8\text{ V}$

$\sin\theta = \dfrac{v}{V_p} = \dfrac{-9.8\text{ V}}{10\text{ V}} = -78.5°$ (on negative half cycle)

$$\text{max. duty cycle } = \left(\frac{360° - 23°}{360°}\right)100 = \mathbf{93.6\%}$$

See Figure 13-9(b).

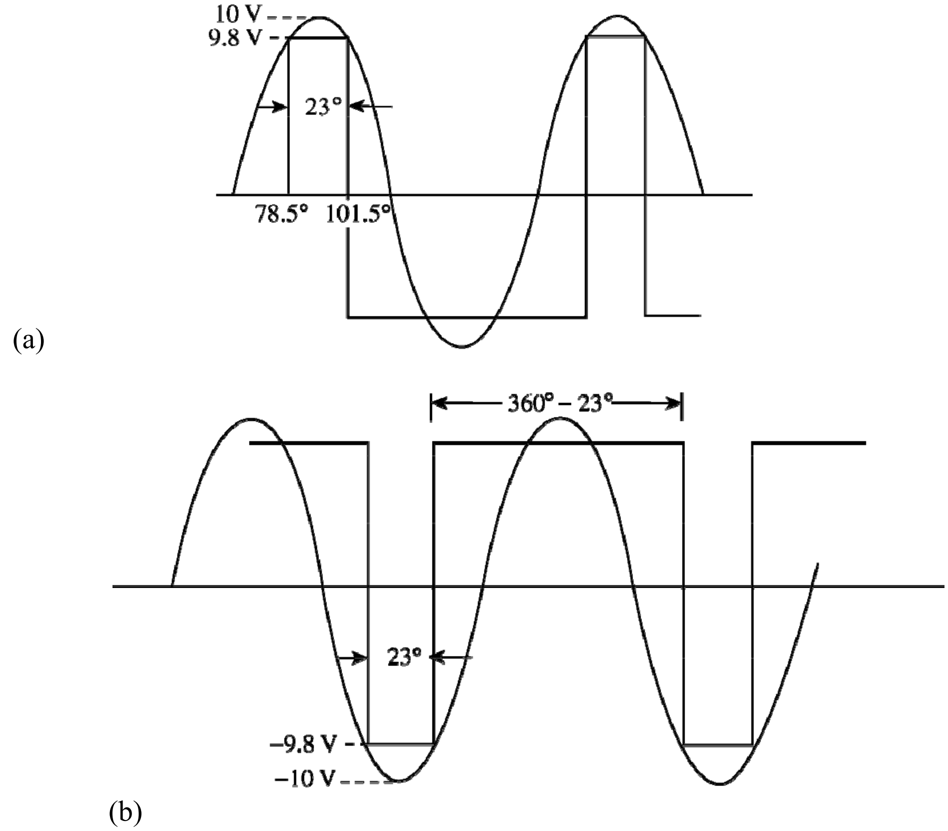

Figure 13-9

28. Let $V_{\text{INV}} = 4.8 \text{ V}$

Let $I_1 = 39.2\ \mu\text{A}$

$V_{\text{INV}} = 12 \text{ V} - I_1R_1$

$-I_1R_1 = 4.8 \text{ V} - 12 \text{ V}$

$I_1R_1 = 7.2 \text{ V}$

$$R_1 = \frac{7.2 \text{ V}}{39.2\ \mu\text{A}} = 184 \text{ k}\Omega$$

Change R_1 and R_3 to $184 \text{ k}\Omega$.

29. $100 \text{ mV}/\mu\text{s} = 5 \text{ V}/R_iC$

$$R_iC = \frac{5 \text{ V}}{100 \text{ mV}/\mu\text{s}}$$

For $C = 3300$ pF:

$$R_i = \frac{50\ \mu\text{s}}{3300\ \text{pF}} = 15.15\ \text{k}\Omega = 15\ \text{k}\Omega + 150\ \Omega$$

For a 5 V peak-peak triangle waveform:

$$t_{ramp\,up} = t_{ramp\,down} = \frac{5\ \text{V}}{100\ \text{mV}/\mu\text{s}} = 50\ \mu\text{s}$$

$$\tau = 2(50\ \mu\text{s}) = 100\ \mu\text{s}$$

$$f_{in} = 1/100\ \mu\text{s} = \mathbf{100\ kHz}$$

See Figure 13-10.

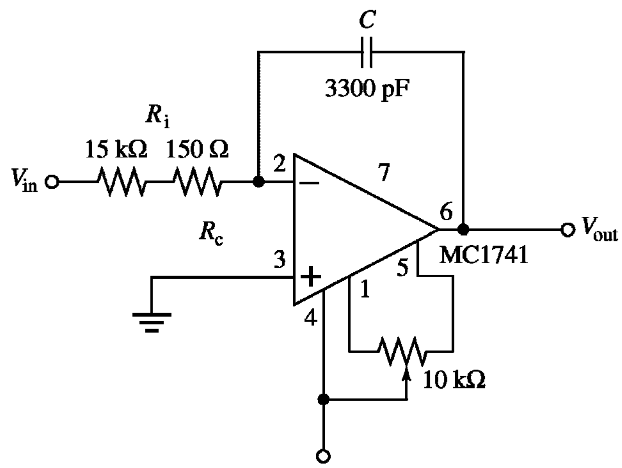

Figure 13-10

Multisim Troubleshooting Problems

30. R_1 open

31. Op-amp inputs shorted together

32. Op-amp + input to output shorted

33. D_1 shorted

34. Top $10\ \text{k}\Omega$ resistor open

35. Middle $10\ \text{k}\Omega$ resistor shorted

36. R_f leaky

37. R_f open

38. C leaky

39. C open

Chapter 14
Special-Purpose Integrated Circuits

Section 14-1 Instrumentation Amplifiers

1. $A_{v(1)} = 1 + \frac{R_1}{R_G} = 1 + \frac{100\text{ k}\Omega}{1.0\text{ k}\Omega} = \mathbf{101}$

$A_{v(2)} = 1 + \frac{R_2}{R_G} = 1 + \frac{100\text{ k}\Omega}{1.0\text{ k}\Omega} = \mathbf{101}$

2. $A_{cl} = 1 + \frac{2R}{R_G} = 1 + \frac{200\text{ k}\Omega}{1.0\text{ k}\Omega} = \mathbf{201}$

3. $V_{out} = A_{cl}(V_{in2} - V_{in1}) = 202(10\text{ mV} - 5\text{ mV}) = \mathbf{1.005\ V}$

4. $A_v = 1 + \frac{2R}{R_G}$

$\frac{2R}{R_G} = A_v - 1$

$R_G = \frac{2R}{A_v - 1} = \frac{2(100\text{ k}\Omega)}{1000 - 1} = \frac{200\text{ k}\Omega}{999} = 200.2\ \Omega \cong \mathbf{200\ \Omega}$

5. $R_G = \frac{50.5\text{ k}\Omega}{A_v - 1}$

$A_v = \frac{50.5\text{ k}\Omega}{1.0\text{ k}\Omega} + 1 = \mathbf{51.5}$

6. Using the graph in textbook Figure 14-6,

$BW \cong \mathbf{300\ kHz}$

7. Change R_G to

$R_G = \frac{50.5\text{ k}\Omega}{A_v - 1} = \frac{50.5\text{ k}\Omega}{24 - 1} \cong \mathbf{2.2\ k\Omega}$

8. $R_G = \frac{50.5\text{ k}\Omega}{A_v - 1} = \frac{50.5\text{ k}\Omega}{20 - 1} \cong \mathbf{2.7\ k\Omega}$

Section 14-2 Isolation Amplifiers

9. $A_{v(total)} = (30)(10) = \mathbf{300}$

10. (a) $A_{v1} = \dfrac{R_{f1}}{R_{i1}} + 1 = \dfrac{18\ \text{k}\Omega}{8.2\ \text{k}\Omega} + 1 = 3.2$

$A_{v2} = \dfrac{R_{f2}}{R_{i2}} + 1 = \dfrac{150\ \text{k}\Omega}{15\ \text{k}\Omega} + 1 = 11$

$A_{v(tot)} = A_{v1}A_{v2} = (3.2)(11) = \mathbf{35.2}$

(b) $A_{v1} = \dfrac{R_{f1}}{R_{i1}} + 1 = \dfrac{330\ \text{k}\Omega}{1.0\ \text{k}\Omega} + 1 = 331$

$A_{v2} = \dfrac{R_{f2}}{R_{i2}} + 1 = \dfrac{47\ \text{k}\Omega}{15\ \text{k}\Omega} + 1 = 4.13$

$A_{v(tot)} = A_{v1}A_{v2} = (331)(4.13) = \mathbf{1367}$

11. $A_{v2} = 11$ (from Problem 10(a))

$A_{v1}A_{v2} = 100$

$\dfrac{R_{f1}}{R_{i1}} + 1 = A_{v1} = \dfrac{100}{11} = 9.09$

$R_{f1} = (9.09 - 1)R_{i1} = (8.09)(8.2\ \text{k}\Omega) = 66\ \text{k}\Omega$

Change R_f (18 kΩ) to 66 kΩ.

Use **68 kΩ** $\pm 1\%$ standard value resistor.

12. $A_{v1} = 331$ (from Problem 10(b))

$A_{v1}A_{v2} = 440$

$\dfrac{R_{f2}}{R_{i2}} + 1 = A_{v2} = \dfrac{440}{331} = 1.33$

Change R_f (47 kΩ) to 3.3 kΩ.

Change R_i (15 kΩ) to 10 kΩ.

13. Connect pin 6 to pin 10 and pin 14 to pin 15. Make $R_f = 0$.

Chapter 14

Section 14-3 Operational Transconductance Amplifiers (OTAs)

14. $$g_m = \frac{I_{out}}{V_{in}} = \frac{10\ \mu\text{A}}{10\ \text{mV}} = \mathbf{1\ mS}$$

15. $$I_{out} = g_m V_{in} = (5000\ \mu\text{S})(100\ \text{mV}) = \mathbf{500\ \mu A}$$

$$V_{out} = I_{out} R_L = (500\ \mu\text{A})(10\ \text{k}\Omega) = \mathbf{5\ V}$$

16. $$g_m = \frac{I_{out}}{V_{in}}$$

$$I_{out} = g_m V_{in} = (4000\ \mu\text{S})(100\ \text{mV}) = 400\ \mu A$$

$$R_L = \frac{V_{out}}{I_{out}} = \frac{3.5\ \text{V}}{400\ \mu\text{A}} = \mathbf{8.75\ k\Omega}$$

17. $$I_{\text{BIAS}} = \frac{+12\ \text{V} - (-12\ \text{V}) - 0.7\ \text{V}}{R_{\text{BIAS}}} = \frac{+12\ \text{V} - (-12\ \text{V}) - 0.7\ \text{V}}{220\ \text{k}\Omega} = \frac{23.3\ \text{V}}{220\ \text{k}\Omega} = 106\ \mu\text{A}$$

From the graph in Figure 14-59:

$$g_m = KI_{\text{BIAS}} \cong (16\ \mu\text{S}/\mu\text{A})(106\ \mu\text{A}) = 1.70\ \text{mS}$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{I_{out} R_L}{V_{in}} = g_m R_L = (1.70\ \text{mS})(6.8\ \text{k}\Omega) = \mathbf{11.6}$$

18. The maximum voltage gain occurs when the $10\ \text{k}\Omega$ potentiometer is set to $0\ \Omega$ and was determined in Problem 17.

$$A_{v(\max)} = \mathbf{11.6}$$

The minimum voltage gain occurs when the $10\ \text{k}\Omega$ potentiometer is set to $10\ \text{k}\Omega$.

$$I_{\text{BIAS}} = \frac{+12\ \text{V} - (-12\ \text{V}) - 0.7\ \text{V}}{220\ \text{k}\Omega + 10\ \text{k}\Omega} = \frac{23.3\ \text{V}}{230\ \text{k}\Omega} = 101\ \mu\text{A}$$

$$g_m \cong (16\ \mu\text{S}/\mu\text{A})(101\ \mu\text{A}) = 1.62\ \text{mS}$$

$$A_{v(\min)} = g_m R_L = (1.62\ \text{mS})(6.8\ \text{k}\Omega) = \mathbf{11.0}$$

19. The V_{MOD} waveform is applied to the bias input.

The gain and output voltage for each value of V_{MOD} is determined as follows using $K = 16\mu\text{S}/\mu\text{A}$. The output waveform is shown in Figure 14-1.

For $V_{\text{MOD}} = +8\ \text{V}$:

$$I_{\text{BIAS}} = \frac{+8\ \text{V} - (-9\ \text{V}) - 0.7\ \text{V}}{39\ \text{k}\Omega} = \frac{16.3\ \text{V}}{39\ \text{k}\Omega} = 418\ \mu\text{A}$$

$$g_m = KI_{\text{BIAS}} \cong (16\ \mu\text{S}/\mu\text{A})(418\ \mu\text{A}) = 6.69\ \text{mS}$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{I_{out}R_L}{V_{in}} = g_m R_L = (6.69\ \text{mS})(10\ \text{k}\Omega) = 66.9$$

$$V_{out} = A_v V_{in} = (66.9)(100\ \text{mV}) = \mathbf{6.69\ V}$$

For $V_{\text{MOD}} = +6\ \text{V}$:

$$I_{\text{BIAS}} = \frac{+6\ \text{V} - (-9\ \text{V}) - 0.7\ \text{V}}{39\ \text{k}\Omega} = \frac{14.3\ \text{V}}{39\ \text{k}\Omega} = 367\ \mu\text{A}$$

$$g_m = KI_{\text{BIAS}} \cong (16\ \mu\text{S}/\mu\text{A})(367\ \mu\text{A}) = 5.87\ \text{mS}$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{I_{out}R_L}{V_{in}} = g_m R_L = (5.87\ \text{mS})(10\ \text{k}\Omega) = 58.7$$

$$V_{out} = A_v V_{in} = (58.7)(100\ \text{mV}) = \mathbf{5.87\ V}$$

For $V_{\text{MOD}} = +4\ \text{V}$:

$$I_{\text{BIAS}} = \frac{+4\ \text{V} - (-9\ \text{V}) - 0.7\ \text{V}}{39\ \text{k}\Omega} = \frac{12.3\ \text{V}}{39\ \text{k}\Omega} = 315\ \mu\text{A}$$

$$g_m = KI_{\text{BIAS}} \cong (16\ \mu\text{S}/\mu\text{A})(315\ \mu\text{A}) = 5.04\ \text{mS}$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{I_{out}R_L}{V_{in}} = g_m R_L = (5.04\ \text{mS})(10\ \text{k}\Omega) = 50.4$$

$$V_{out} = A_v V_{in} = (50.4)(100\ \text{mV}) = \mathbf{5.04\ V}$$

For $V_{\text{MOD}} = +2\ \text{V}$:

$$I_{\text{BIAS}} = \frac{+2\ \text{V} - (-9\ \text{V}) - 0.7\ \text{V}}{39\ \text{k}\Omega} = \frac{10.3\ \text{V}}{39\ \text{k}\Omega} = 264\ \mu A$$

$$g_m = KI_{\text{BIAS}} \cong (16\ \mu\text{S}/\mu\text{A})(264\ \mu\text{A}) = 4.22\ \text{mS}$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{I_{out}R_L}{V_{in}} = g_m R_L = (4.22\ \text{mS})(10\ \text{k}\Omega) = 42.2$$

$$V_{out} = A_v V_{in} = (42.2)(100\ \text{mV}) = \mathbf{4.22\ V}$$

For $V_{\text{MOD}} = +1\ \text{V}$:

$$I_{\text{BIAS}} = \frac{+1\ \text{V} - (-9\ \text{V}) - 0.7\ \text{V}}{39\ \text{k}\Omega} = \frac{9.3\ \text{V}}{39\ \text{k}\Omega} = 238\ \mu\text{A}$$

$$g_m = KI_{\text{BIAS}} \cong (16\ \mu\text{S}/\mu\text{A})(238\ \mu\text{A}) = 3.81\ \text{mS}$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{I_{out}R_L}{V_{in}} = g_m R_L = (3.81\ \text{mS})(10\ \text{k}\Omega) = 38.1$$

$$V_{out} = A_v V_{in} = (38.1)(100\ \text{mV}) = \mathbf{3.81\ V}$$

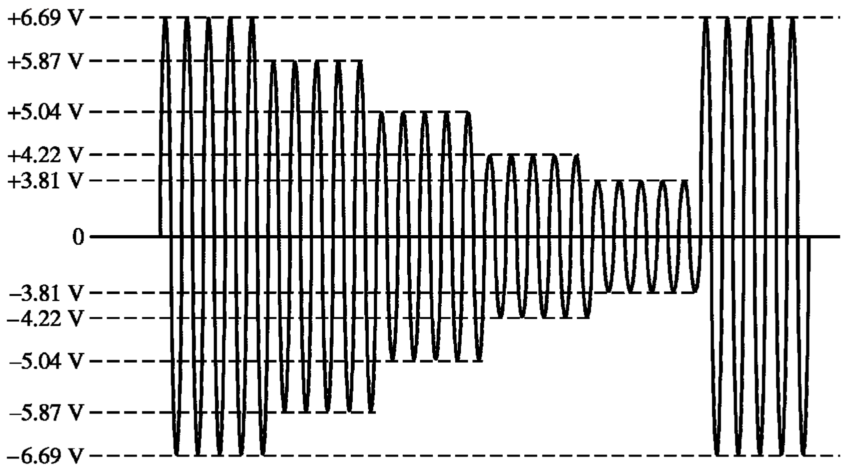

Figure 14-1

20. $$I_{BIAS} = \frac{+9\text{V} - (-9\text{ V}) - 0.7\text{ V}}{39\text{ k}\Omega} = \frac{17.3\text{ V}}{39\text{ k}\Omega} = 444\ \mu\text{A}$$

$$V_{\text{TRIG}(+)} = I_{\text{BIAS}}R_1 = (444\ \mu\text{A})(10\text{ k}\Omega) = \mathbf{+4.44\ V}$$

$$V_{\text{TRIG}(-)} = I_{\text{BIAS}}R_1 = (-444\ \mu\text{A})(10\text{ k}\Omega) = \mathbf{-4.44\ V}$$

21. See Figure 14-2.

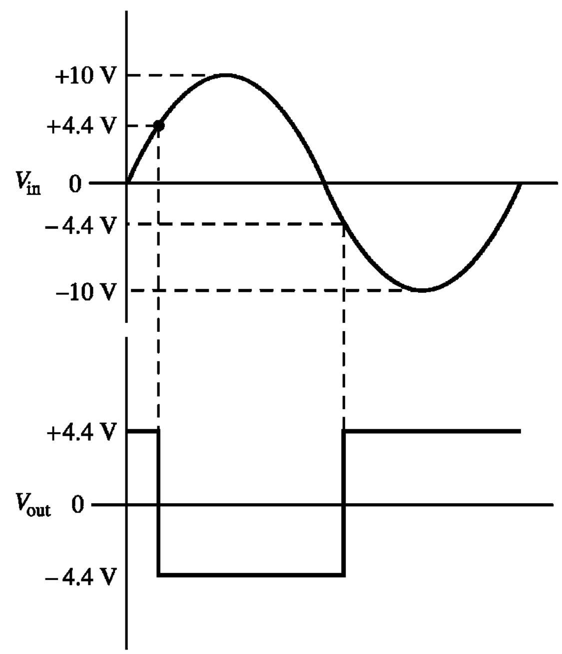

Figure 14-2

Section 14-4 Log and Antilog Amplifiers

22. (a) $\ln(0.5) = \mathbf{-0.693}$

(b) $\ln(2) = \mathbf{0.693}$

(c) $\ln(50) = \mathbf{3.91}$

(d) $\ln(130) = \mathbf{4.87}$

23. (a) $\log_{10}(0.5) = \mathbf{-0.301}$

(b) $\log_{10}(2) = \mathbf{0.301}$

(c) $\log_{10}(50) = \mathbf{1.70}$

(d) $\log_{10}(130) = \mathbf{2.11}$

24. Antilog $x = 10^x$ or e^x, depending on the base used.

$\text{INV}\ln = e^{1.6} = \mathbf{4.95}$

$\text{INV}\log = 10^{1.6} = \mathbf{39.8}$

25. The output of a log amplifier is limited to **0.7 V** because the output voltage is limited to the barrier potential of the transistor's *pn* junction.

26.
$$V_{out} \cong -(0.025\text{ V})\ln\left(\frac{V_{in}}{I_s R_{in}}\right)$$
$$= -(0.025\text{ V})\ln\left(\frac{3\text{ V}}{(100\text{ nA})(82\text{ k}\Omega)}\right) = -(0.025\text{ V})\ln(365.9) = \mathbf{-148\text{ mV}}$$

27.
$$V_{out} \cong -(0.025\text{ V})\ln\left(\frac{V_{in}}{I_{\text{EBO}} R_{in}}\right)$$
$$-(0.025\text{V})\ln\left(\frac{1.5\text{ V}}{(60\text{ nA})(47\text{ k}\Omega)}\right) = -(0.025\text{ V})\ln(531.9) = \mathbf{-157\text{ mV}}$$

28.
$$V_{out} = -R_f I_{EBO}\text{antilog}\left(\frac{V_{in}}{25\text{ mV}}\right) = -R_f I_{\text{EBO}} e^{\left(\frac{V_{in}}{25\text{ mV}}\right)}$$
$$V_{out} = -(10\text{ k}\Omega)(60\text{ nA})e^{\left(\frac{0.225\text{ V}}{25\text{ mV}}\right)} = -(10\text{ k}\Omega)(60\text{ nA})e^9 = -(10\text{ k}\Omega)(60\text{ nA})(8103) = \mathbf{-4.86\text{ V}}$$

29.
$$V_{out(max)} \cong -(0.025\text{ V})\ln\left(\frac{V_{in}}{I_{\text{EBO}} R_{in}}\right) = -(0.025\text{ V}\ln\left(\frac{1\text{ V}}{(60\text{ nA}(47\text{ k}\Omega)}\right)$$
$$= -(0.025\text{ V})\ln(354.6) = \mathbf{-147\text{ mV}}$$
$$V_{out(min)} \cong -(0.025\text{ V})\ln\left(\frac{V_{in}}{I_{\text{EBO}} R_{in}}\right) = -(0.025\text{ V})\ln\left(\frac{100\text{ mV}}{(60\text{ nA})(47\text{ k}\Omega)}\right)$$
$$= -(0.025\text{ V})\ln(35.5) = \mathbf{-89.2\text{ mV}}$$

The signal compression allows larger signals to be reduced without causing smaller amplitudes to be lost (in this case, the 1 V peak is reduced 85% but the 100 mV peak is reduced only 10%).

Section 14-5 Converters and Other Integrated Circuits

30. (a) $V_{IN} = V_Z = 4.7\text{ V}$

$$I_L = \frac{V_{IN}}{R_i} = \frac{4.7\text{ V}}{1.0\text{ k}\Omega} = \mathbf{4.7\ mA}$$

(b) $V_{IN} = \left(\dfrac{10\text{ k}\Omega}{20\text{ k}\Omega}\right)12\text{ V} = 6\text{ V}$

$$R_i = 10\text{ k}\Omega \,\|\, 10\text{ k}\Omega + 100\ \Omega = 5.1\text{ k}\Omega$$

$$I_L = \frac{V_{IN}}{R_i} = \frac{6\text{ V}}{5.1\text{ k}\Omega} = \mathbf{1.18\ mA}$$

31. See Figure 14-3.

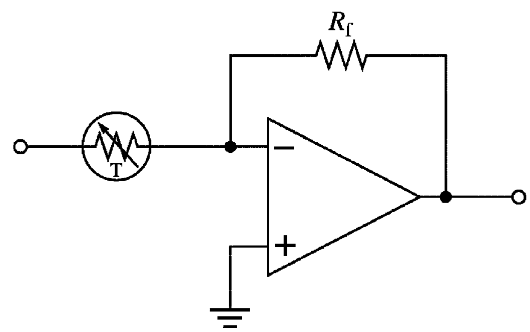

Figure 14-3

Multisim Troubleshooting Problems

32. R_G leaky

33. R open

34. R_f open

35. Zener diode open

36. Lower $10\text{ k}\Omega$ resistor open

Chapter 15
Active Filters

Section 15-1 Basic Filter Responses

1. (a) Band-pass

(b) High-pass

(c) Low-pass

(d) Band-stop

2. $BW = f_c = \mathbf{800\ Hz}$

3. $f_c = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi(2.2\ \text{k}\Omega)(0.0015\ \mu\text{F})} = \mathbf{48.2\ Hz}$

No, the upper response roll-off due to internal device capacitances is unknown.

4. The roll-off is **20 dB/decade** because this is a single-pole filter.

5. $BW = f_{c2} - f_{c1} = 3.9\ \text{kHz} - 3.2\ \text{kHz} = 0.7\ \text{kHz} = \mathbf{700\ Hz}$

$f_0 = \sqrt{f_{c1} f_{c2}} = \sqrt{(3.2\ \text{kHz})(3.9\ \text{kHz})} = 3.53\ \text{kHz}$

$Q = \dfrac{f_0}{BW} = \dfrac{3.53\ \text{kHz}}{700\ \text{Hz}} = \mathbf{5.04}$

6. $Q = \dfrac{f_0}{BW}$

$f_0 = Q(BW) = 15(1\ \text{kHz}) = \mathbf{15\ kHz}$

Section 15-2 Filter Response Characteristics

7. (a) 2nd order, 1 stage

$DF = 2 - \dfrac{R_3}{R_4} = 2 - \dfrac{1.2\ \text{k}\Omega}{1.2\ \text{k}\Omega} = 2 - 1 = \mathbf{1}$ **Not Butterworth**

(b) 2nd order, 1 stage

$DF = 2 - \dfrac{R_3}{R_4} = 2 - \dfrac{560\ \Omega}{1.0\ \text{k}\Omega} = 2 - 0.56 = \mathbf{1.44}$ **Approximately Butterworth**

(c) 3rd order, 2 stages, 1st stage (2 poles):

$$DF = 2 - \frac{R_3}{R_4} = 2 - \frac{330\ \Omega}{1.0\ \text{k}\Omega} = \mathbf{1.67}$$

2nd stage (1 pole):

$$DF = 2 - \frac{R_6}{R_7} = \mathbf{1.67}$$ **Not Butterworth**

8. (a) and (c) are low-pass; (b) is high-pass.

9. (a) and (b) are two-pole filters with approximately a –40 dB/decade roll-off. (c) is a three-pole filter with approximately a –60 dB/decade roll-off rate.

10. (a) From Table 15-1 in the textbook, the damping factor must be 1.414; therefore,

$$\frac{R_3}{R_4} = 0.586$$

$$R_3 = 0.586 R_4 = 0.586(1.2\ \text{k}\Omega) = \mathbf{703\ \Omega}$$

Nearest standard value: **720 Ω**

(b) $$\frac{R_3}{R_4} = 0.56$$

This is an approximate Butterworth response

(as close as you can get using standard 5% resistors).

(c) From Table 15-1, the damping factor of both stages must be 1, therefore

$$\frac{R_3}{R_4} = 1$$

$$R_3 = R_4 = R_6 = R_7 = \mathbf{1\ k\Omega}\ \text{(for both stages)}$$

11. (a) Chebyshev

(b) Butterworth

(c) Bessel

(d) Butterworth

Section 15-3 Active Low-Pass Filters

12. **High Pass**

1st stage:

$$DF = 2 - \frac{R_3}{R_4} = 2 - \frac{1.0\ \text{k}\Omega}{6.8\ \text{k}\Omega} = 1.85$$

2nd stage:

$$DF = 2 - \frac{R_7}{R_8} = 2 - \frac{6.8\ \text{k}\Omega}{5.6\ \text{k}\Omega} = 0.786$$

From Table 15-1 in the textbook:

1st stage DF = 1.848 and 2nd stage DF = 0.765

Therefore, this filter is **approximately Butterworth**.

Roll-off rate = **80 dB/decade**

13. $$f_c = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}} = \frac{1}{2\pi\sqrt{R_5R_6C_3C_4}} = \frac{1}{2\pi\sqrt{(4.7\ \text{k}\Omega)(6.8\ \text{k}\Omega)(0.22\ \mu\text{F})(0.1\ \mu\text{F})}} = \mathbf{190\ Hz}$$

14. $R = R_1 = R_2 = R_5 = R_6$ and $C = C_1 = C_2 = C_3 = C_4$

Let $C = \mathbf{0.22\ \mu F}$ (for both stages).

$$f_c = \frac{1}{2\pi\sqrt{R^2C^2}} = \frac{1}{2\pi RC}$$

$$R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi(190\ \text{Hz})(0.22\ \mu\text{F})} = 3.81\ \text{k}\Omega$$

Choose R = **3.9 kΩ** (for both stages)

15. Add another identical stage and change the ratio of the feedback resistors to 0.068 for first stage, 0.586 for second stage, and 1.482 for third stage. See Figure 15-1.

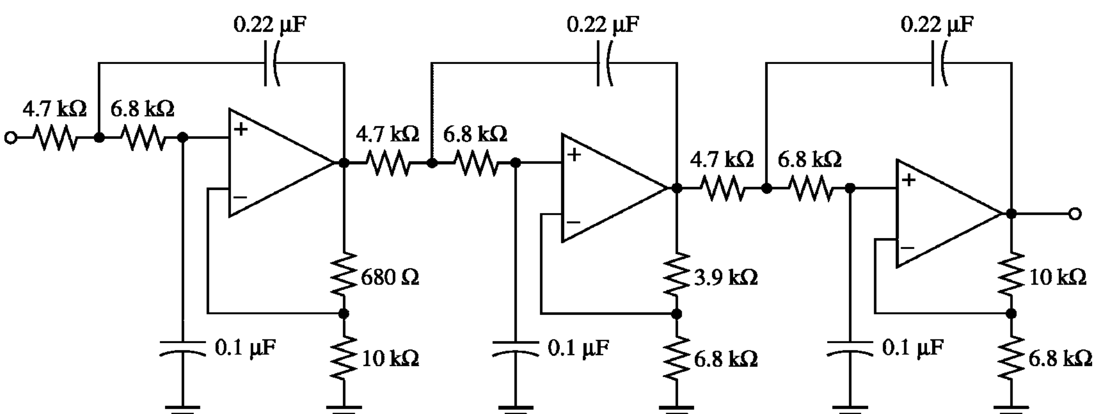

Figure 15-1

16. See Figure 15-2.

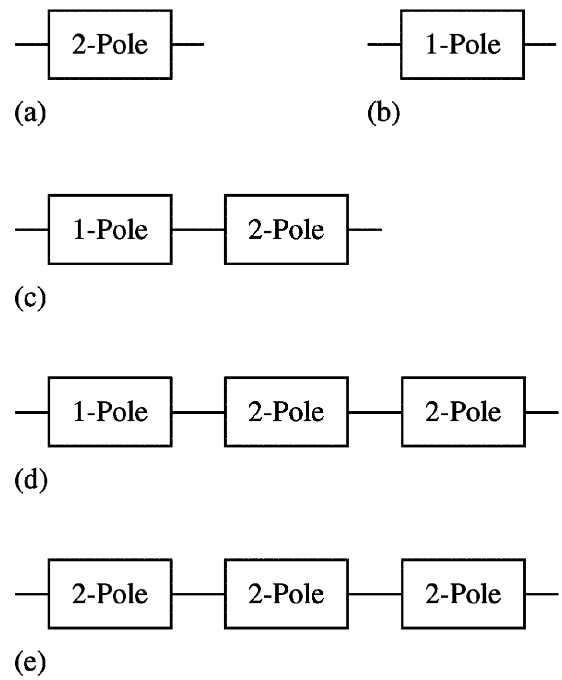

Figure 15-2

Section 15-4 Active High-Pass Filters

17. Exchange the positions of the resistors and the capacitors. See Figure 15-3.

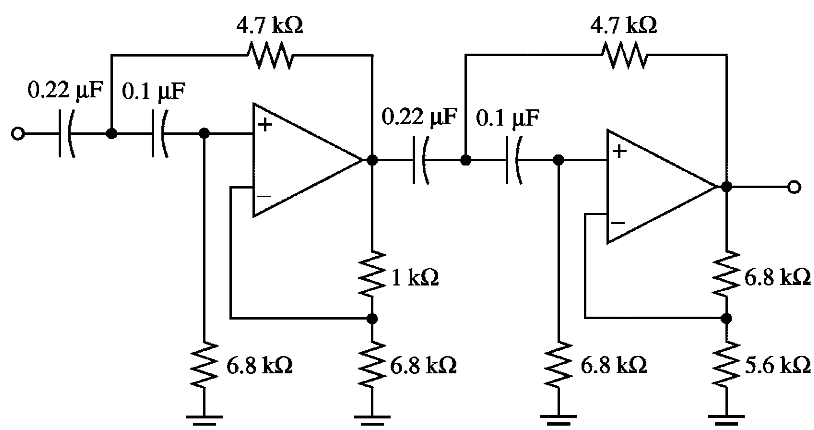

Figure 15-3

18. $$f_c = \frac{1}{2\pi RC}$$

$$f_0 = \frac{190 \text{ Hz}}{2} = 95 \text{ Hz}$$

$$R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi(95\text{ Hz})(0.22\ \mu\text{F})} = 7615\ \Omega$$

Let R = 7.5 kΩ. Change R_1, R_2, R_5 and R_6 to **7.5 kΩ**.

19. (a) Decrease R_1 and R_2 or C_1 and C_2.

(b) Increase R_3 or decrease R_4.

Section 15-5 Active Band-Pass Filters

20. (a) Cascaded high-pass/low-pass filters

(b) Multiple feedback

(c) State variable

21. (a) 1st stage:

$$f_{c1} = \frac{1}{2\pi RC} = \frac{1}{2\pi(1.0\text{ k}\Omega)(0.047\ \mu\text{F})} = 3.39\text{ kHz}$$

2nd stage:

$$f_{c2} = \frac{1}{2\pi RC} = \frac{1}{2\pi(1.0\text{ k}\Omega)(0.022\ \mu\text{F})} = 7.23\text{ kHz}$$

$$f_0 = \sqrt{f_{c1}f_{c2}} = \sqrt{(3.39\text{ kHz})(7.23\text{ kHz})} = \mathbf{4.95\ kHz}$$

$$BW = 7.23\text{ kHz} - 3.39\text{ Hz} = \mathbf{3.84\ kHz}$$

(b) $$f_0 = \frac{1}{2\pi C}\sqrt{\frac{R_1 + R_3}{R_1 R_3 R_2}} = \frac{1}{2\pi(0.022\ \mu\text{F})}\sqrt{\frac{47\text{ k}\Omega + 1.8\text{ k}\Omega}{(47\text{ k}\Omega)(1.8\text{ k}\Omega)(150\text{ k}\Omega)}} = \mathbf{449\ Hz}$$

$$Q = \pi f_0 C R_2 = \pi(449\text{ Hz})(0.022\ \mu\text{F})(150\text{ k}\Omega) = 4.66$$

$$BW = \frac{f_0}{Q} = \frac{449\text{ Hz}}{4.66} = \mathbf{96.4\ Hz}$$

(c) For each integrator:

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi(10\text{ k}\Omega)(0.001\ \mu\text{F})} = 15.9\text{ kHz}$$

$$f_0 = f_c = \mathbf{15.9\ kHz}$$

$$Q = \frac{1}{3}\left(\frac{R_5}{R_6} + 1\right) = \frac{1}{3}\left(\frac{560\text{ k}\Omega}{10\text{ k}\Omega} + 1\right) = \frac{1}{3}(56 + 1) = 19$$

$$BW = \frac{f_0}{Q} = \frac{15.9\text{ kHz}}{19} = \mathbf{838\ Hz}$$

22. $Q = \frac{1}{3}\left(\frac{R_5}{R_6} + 1\right)$

Select $R_6 = \mathbf{10\ k\Omega}$.

$$Q = \frac{R_5}{3R_6} + \frac{1}{3} = \frac{R_5 + R_6}{3R_6}$$

$$3R_6Q = R_5 + R_6$$

$$R_5 = 3R_6Q - R_6 = 3(10\ \text{k}\Omega)(50) - 10\ \text{k}\Omega = 1500\ \text{k}\Omega - 10\ \text{k}\Omega = \mathbf{1490\ k\Omega}$$

$$f_0 = \frac{1}{2\pi(12\ \text{k}\Omega)(0.01\ \mu\text{F})} = 1.33\ \text{kHz}$$

$$BW = \frac{f_0}{Q} = \frac{1.33\ \text{kHz}}{50} = \mathbf{26.6\ Hz}$$

Section 15-6 Active Band-Stop Filters

23. See Figure 15-4.

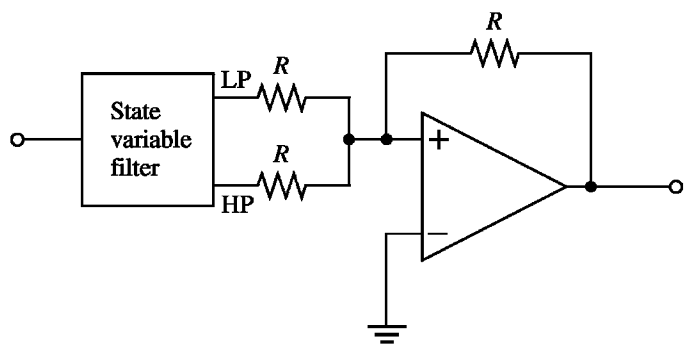

Figure 15-4

24. $f_0 = f_c = \frac{1}{2\pi RC}$

Let C remain 0.01 μF.

$$R = \frac{1}{2\pi f_0 C} = \frac{1}{2\pi(120\ \text{Hz})(0.01\ \mu\text{F})} = \mathbf{133\ k\Omega}$$

Change R in the integrators from 12 kΩ to 133 kΩ.

Multisim Troubleshooting Problems

25. R_4 shorted

26. R_3 open

27. C_3 shorted

28. R_5 open

29. R_1 open

30. R_2 shorted

31. R_1 open

32. C_2 open

33. R_7 open

Chapter 16
Oscillators

Section 16-1 The Oscillator

1. An oscillator requires no input other than the dc supply voltage.

2. Amplifier and positive feedback circuit

Section 16-2 Feedback Oscillators

3. Unity gain around the closed loop is required for sustained oscillation.

$$A_{cl} = A_v B = 1$$

$$B = \frac{1}{A_v} = \frac{1}{75} = \mathbf{0.0133}$$

4. To ensure startup:

$$A_{cl} > 1$$

since $A_v = 75$, B must be greater than 1/75 in order to produce the condition

$A_v B > 1.$

For example, if $B = 1/50$,

$$A_v B = 75\left(\frac{1}{50}\right) = 1.5$$

Section 16-3 Oscillators with RC Feedback Circuits

5. $$\frac{V_{out}}{V_{in}} = \frac{1}{3}$$

$$V_{out} = \left(\frac{1}{3}\right)V_{in} = \frac{2.2\text{ V}}{3} = \mathbf{733\ mV}$$

6. $$f_r = \frac{1}{2\pi RC} = \frac{1}{2\pi(6.2\text{ k}\Omega)(0.02\ \mu\text{F})} = \mathbf{1.28\ kHz}$$

7. $$f_{r(min)} = \frac{1}{2\pi R_{(max)}C} = \frac{1}{2\pi(6.4\text{ k}\Omega)(0.1\ \mu\text{F})} = \mathbf{249\ Hz}$$

$$f_{r(max)} = \frac{1}{2\pi R_{(min)}C} = \frac{1}{2\pi(5.9\text{ k}\Omega)(0.1\ \mu\text{F})} = \mathbf{270\ Hz}$$

8. $$A_{cl} = \frac{R_1 + R_2}{R_2} = \frac{R_1}{R_2} + 1$$

$$R_1 = R_2(A_{cl} - 1)$$

Substitute $R_f = R_1; R_2 = R_{lamp}$ and solve for R_f:

$$R_f = R_{lamp}(A_{CL} - 1) = 160\ \Omega\ (3-1) = \mathbf{320\ \Omega}$$

9. $$R_f = (A_v - 1)(R_3 + r'_{ds}) = (3-1)(820\,\Omega + 350\,\Omega) = \mathbf{2.34\ k\Omega}$$

10. $$f_r = \frac{1}{2\pi(1.0\text{ k}\Omega)(0.015\mu\text{F})} = \mathbf{10.6\ kHz}$$

11. $$B = \frac{1}{29}$$

$$A_{cl} = \frac{1}{B} = 29$$

$$A_{cl} = \frac{R_f}{R_i}$$

$$R_f = A_{cl}R_i = 29(4.7\text{ k}\Omega) = \mathbf{136\ k\Omega}$$

$$f_r = \frac{1}{2\pi\sqrt{6}(4.7\text{ k}\Omega)(0.022\ \mu\text{F})} = \mathbf{628\ Hz}$$

Section 16-4 Oscillators with LC Feedback Circuits

12. (a) *Colpitts*: C_1 and C_3 are the feedback capacitors.

$$f_r = \frac{1}{2\pi\sqrt{L_1C_T}}$$

$$C_T = \frac{C_1C_3}{C_1 + C_3} = \frac{(100\ \mu\text{F})(1000\text{ pF})}{1100\text{ pF}} = 90.9\text{ pF}$$

$$f_r = \frac{1}{2\pi\sqrt{(5\text{ mH})90.9\text{ pF})}} = \mathbf{236\ kHz}$$

(b) *Hartley*:

$$f_r = \frac{1}{2\pi\sqrt{L_T C_2}}$$

$$L_T = L_1 + L_2 = 1.5 \text{ mH} + 10 \text{ mH} = 11.5 \text{ mH}$$

$$f_r = \frac{1}{2\pi\sqrt{(11.5 \text{ mH})(470 \text{pF})}} = \mathbf{68.5\,kHz}$$

13. $B = \dfrac{47 \text{ pF}}{470 \text{ pF}} = 0.1$

The condition for sustained oscillation is

$$A_v = \frac{1}{B} = \frac{1}{0.1} = \mathbf{10}$$

Section 16-5 Relaxation Oscillators

14. Triangular waveform.

$$f = \frac{1}{4R_1C}\left(\frac{R_2}{R_3}\right) = \frac{1}{4(22\,\text{k}\Omega)(0.22\,\mu\text{F})}\left(\frac{56\,\text{k}\Omega}{18\,\text{k}\Omega}\right) = \mathbf{1.61\,kHz}$$

15. Change f to 10 kHz by changing R_1:

$$f = \frac{1}{4R_1C}\left(\frac{R_2}{R_3}\right)$$

$$R_1 = \frac{1}{4fC}\left(\frac{R_2}{R_3}\right) = \frac{1}{4(10\,\text{kHz})(0.022\,\mu\text{F})}\left(\frac{56\,\text{k}\Omega}{18\,\text{k}\Omega}\right) = \mathbf{3.54\,k\Omega}$$

16. $T = \dfrac{V_p - V_F}{\left(\dfrac{|V_{IN}|}{RC}\right)}$

$$V_p = \left(\frac{R_5}{R_4 + R_5}\right)12 \text{ V} = \left(\frac{47\,\text{k}\Omega}{147\,\text{k}\Omega}\right)12 \text{ V} = 3.84 \text{ V}$$

PUT triggers at about +3.84 V (ignoring the 0.7 V drop)

Amplitude = +3.84 V – 1 V = **2.84 V**

$$V_{IN} = \left(\frac{R_2}{R_1 + R_2}\right)(-12 \text{ V}) = \left(\frac{22\,\text{k}\Omega}{122\,\text{k}\Omega}\right)(-12 \text{ V}) = -2.16 \text{ V}$$

$$T = \frac{3.84\text{ V} - 1\text{ V}}{\left(\dfrac{2.16\text{ V}}{(100\text{ k}\Omega)(0.0022\,\mu\text{F})}\right)} = 289\ \mu\text{s}$$

$$f = \frac{1}{T} = \frac{1}{289\ \mu\text{s}} = \mathbf{3.46\ kHz}$$

See Figure 16-1.

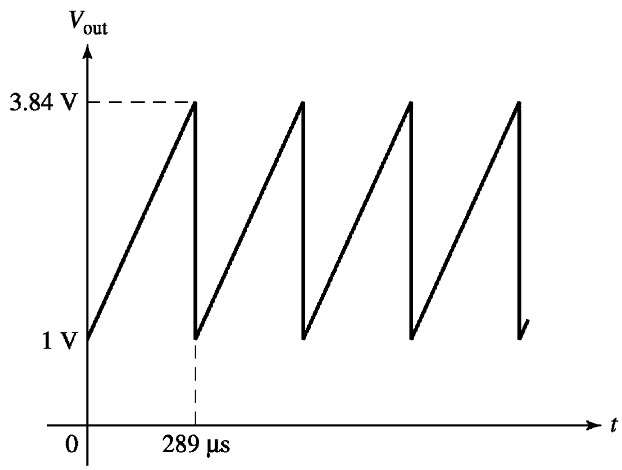

Figure 16-1

17. $V_G = 5$ V. Assume $V_{AK} = 1$ V.

$R_5 = 47\text{ k}\Omega$

$$V_G = \left(\frac{R_5}{R_4 + R_5}\right)12\text{ V}$$

Change R_4 to get $V_G = 5$ V.

$$5\text{ V}(R_4 + 47\text{ k}\Omega) = (47\text{ k}\Omega)12\text{ V}$$

$$R_4(5\text{ V}) = (47\text{ k}\Omega)12\text{ V} - (47\text{ k}\Omega)5\text{ V}$$

$$R_4 = \frac{(12\text{ V} - 5\text{ V})47\text{ k}\Omega}{5\text{ V}} = \mathbf{65.8\ k\Omega}$$

18. $$T = \frac{V_p - V_F}{\left(\dfrac{V_{IN}}{RC}\right)}$$

$$V_p = \left(\frac{V_{IN}}{RC}\right)T + V_F = \left(\frac{3\text{ V}}{(4.7\text{ k}\Omega)(0.001\,\mu\text{F})}\right)10\ \mu\text{s} + 1\text{ V} = 7.38\text{ V}$$

$$V_{pp(out)} = V_p - V_F = 7.38\text{ V} - 1\text{ V} = \mathbf{6.38\ V}$$

Chapter 16

Section 16-6 The 555 Timer as an Oscillator

19. $\frac{1}{3}V_{CC} = \frac{1}{3}(10 \text{ V}) = \mathbf{3.33\ V}$

$\frac{2}{3}V_{CC} = \frac{2}{3}(10 \text{ V}) = \mathbf{6.67\ V}$

20. $f = \dfrac{1.44}{(R_1 + 2R_2)C_{ext}} = \dfrac{1.44}{(1.0 \text{ k}\Omega + 6.6 \text{ k}\Omega)(0.047\ \mu\text{F})} = \mathbf{4.03\ kHz}$

21. $f = \dfrac{1.44}{(R_1 + 2R_2)C_{ext}}$

$C_{ext} = \dfrac{1.44}{(R_1 + 2R_2)f} = \dfrac{1.44}{(1.0 \text{ k}\Omega + 6.6 \text{ k}\Omega)(25 \text{ kHz})} = \mathbf{0.0076\ \mu F}$

22. Duty cycle (dc) $= \dfrac{R_1 + R_2}{R_1 + 2R_2} \times 100\%$

$\text{dc}(R_1 + 2R_2) = (R_1 + R_2)100$

$75(3.3 \text{ k}\Omega + 2R_2) = (3.3 \text{ k}\Omega + R_2)100$

$75(3.3 \text{ k}\Omega) + 150R_2 = 100(3.3 \text{ k}\Omega) + 100R_2$

$150R_2 - 100R_2 = 100(3.3 \text{ k}\Omega) - 75(3.3 \text{ k}\Omega)$

$50R_2 = 25(3.3 \text{ k}\Omega)$

$R_2 = \dfrac{25(3.3 \text{ k}\Omega)}{50} = \mathbf{1.65\ k\Omega}$

Multisim Troubleshooting Problems

23. Drain-to-source shorted

24. C_3 open

25. Collector-to-emitter shorted

26. R_1 open

27. R_2 open

28. R_1 leaky

Chapter 17
Voltage Regulators

Section 17-1 Voltage Regulation

1. Percent line regulation $= \left(\dfrac{\Delta V_{\mathrm{OUT}}}{\Delta V_{\mathrm{IN}}}\right)100\% = \left(\dfrac{2\text{ mV}}{6\text{ V}}\right)100\% = \mathbf{0.0333\%}$

2. Percent line regulation $= \left(\dfrac{\Delta V_{\mathrm{OUT}}/V_{\mathrm{OUT}}}{\Delta V_{\mathrm{IN}}}\right)100\% = \left(\dfrac{2\text{ mV}/8\text{ V}}{6\text{ V}}\right)100\% = \mathbf{0.00417\%\ /\ V}$

3. Percent load regulation $= \left(\dfrac{V_{\mathrm{NL}}/V_{\mathrm{FL}}}{\Delta V_{\mathrm{FL}}}\right)100\% = \left(\dfrac{10\text{ V} - 9.90\text{ V}}{9.90\text{ V}}\right)100\% = \mathbf{1.01\%}$

4. From Problem 3, the percent load regulation is 1.01%. For a full load current of 250 mA, this can be expressed as

$$\frac{1.01\%}{250\text{ mA}} = \mathbf{0.00404\%\ /\ mA}$$

Section 17-2 Basic Linear Series Regulators

5. See Figure 17-1.

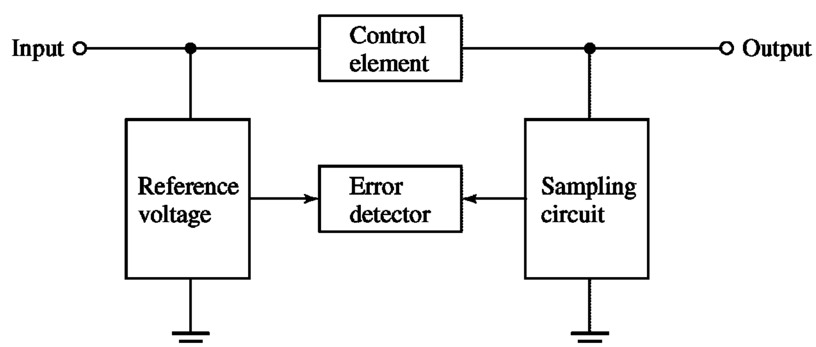

Figure 17-1

6. $V_{\mathrm{OUT}} = \left(1 + \dfrac{R_2}{R_3}\right)V_{\mathrm{REF}} = \left(1 + \dfrac{33\text{ k}\Omega}{10\text{ k}\Omega}\right)2.4\text{ V} = \mathbf{10.3\ V}$

7. $V_{\mathrm{OUT}} = \left(1 + \dfrac{R_2}{R_3}\right)V_{\mathrm{REF}} = \left(1 + \dfrac{5.6\text{ k}\Omega}{2.2\text{ k}\Omega}\right)2.4\text{ V} = \mathbf{8.51\ V}$

8. For $R_3 = 2.2\ \text{k}\Omega$:

$$V_{\text{OUT}} = \left(1+\frac{R_2}{R_3}\right)V_{\text{REF}} = \left(1+\frac{5.6\ \text{k}\Omega}{2.2\ \text{k}\Omega}\right)2.4\ \text{V} = 8.5\ \text{V}$$

For $R_3 = 4.7\ \text{k}\Omega$:

$$V_{\text{OUT}} = \left(1+\frac{R_2}{R_3}\right)V_{\text{REF}} = \left(1+\frac{5.6\ \text{k}\Omega}{4.7\ \text{k}\Omega}\right)2.4\ \text{V} = 5.26\ \text{V}$$

The output voltage **decreases by 3.24 V** when R_3 is changed from 2.2 kΩ to 4.7 kΩ.

9. $$V_{\text{OUT}} = \left(1+\frac{R_2}{R_3}\right)V_{\text{REF}} = \left(1+\frac{5.6\ \text{k}\Omega}{2.2\ \text{k}\Omega}\right)2.7\ \text{V} = \mathbf{9.57\ V}$$

10. $$I_{\text{L(max)}} = \frac{0.7\ \text{V}}{R_4}$$

$$R_4 = \frac{0.7\ \text{V}}{I_{\text{L(max)}}} = \frac{0.7\ \text{mA}}{250\ \text{mA}} = \mathbf{2.8\ \Omega}$$

$$P = I^2_{\text{L(max)}}R_4 = (250\ \text{mA})^2 2.8\ \Omega = \mathbf{0.175\ W}.\ \text{Use a 0.25 W.}$$

11. $$R_4 = \frac{2.8\ \Omega}{2} = 1.4\ \Omega$$

$$I_{\text{L(max)}} = \frac{0.7\ \text{V}}{R_4} = \frac{0.7\ \text{V}}{1.4\ \Omega} = \mathbf{500\ mA}$$

Section 17-3 Basic Linear Shunt Regulators

12. Q_1 conducts more when the load current increases, assuming that the output voltage attempts to increase. When the output voltage tries to increase due to a change in load current, the attempted increase is sensed by R_3 and R_4 and a proportional voltage is applied to the op-amp's non-inverting input. The resulting difference voltage increases the op-amp output, driving Q_1 more and thus increasing its collector current.

13. $$\Delta I_{\text{C}} = \frac{\Delta V_{\text{R1}}}{R_1} = \frac{1\ \text{V}}{100\ \Omega} = \mathbf{10\ mA}$$

14. $$V_{\text{OUT}} = \left(1+\frac{R_3}{R_4}\right)V_{\text{REF}} = \left(1+\frac{10\ \text{k}\Omega}{3.9\ \text{k}\Omega}\right)5.1\ \text{V} = \mathbf{18.2\ V}$$

$$I_{L1} = \frac{V_{\text{OUT}}}{R_{\text{L1}}} = \frac{18.2\ \text{V}}{1\ \text{k}\Omega} = 18.2\ \text{mA}$$

$$I_{L2} = \frac{V_{\text{OUT}}}{R_{\text{L2}}} = \frac{18.2\ \text{V}}{1.2\ \text{k}\Omega} = 15.2\ \text{mA}$$

$\Delta I_{\text{L}} = 15.2\text{ mA} - 18.2\text{ mA} = -3.0\text{ mA}$

$\Delta I_{\text{S}} = -\Delta I_{\text{L}} = \mathbf{3.0\,mA}$

15. $I_{\text{L(max)}} = \dfrac{V_{\text{IN}}}{R_1} = \dfrac{25\text{ V}}{100\ \Omega} = \mathbf{250\,mA}$

$P_{\text{R1}} = I^2_{\text{L(max)}}R_1 = (250\text{ mA})^2 100\ \Omega = \mathbf{6.25\,W}$

Section 17-4 Basic Switching Regulators

16. $V_{\text{OUT}} = \left(\dfrac{t_{on}}{T}\right)V_{\text{IN}}$

$t_{on} = T - t_{off}$

$T = \dfrac{1}{f} = \dfrac{1}{10\text{ kHz}} = 0.0001\text{ s} = 100\ \mu\text{s}$

$V_{\text{OUT}} = \left(\dfrac{40\ \mu\text{s}}{100\ \mu\text{s}}\right)12\text{ V} = \mathbf{4.8\,V}$

17. $f = 100\text{ Hz},\ t_{off} = 6\text{ ms}$

$T = \dfrac{1}{f} = \dfrac{1}{100\text{ Hz}} = 10\text{ ms}$

$t_{on} = T - t_{off} = 10\text{ ms} - 6\text{ ms} = 4\text{ ms}$

$\text{duty cycle} = \dfrac{t_{on}}{T} = \dfrac{4\text{ ms}}{10\text{ ms}} = 0.4$

$\text{percent duty cycle} = 0.4 \times 100\% = \mathbf{40\%}$

18. The diode D_1 becomes forward-biased when Q_1 turns off.

19. The output voltage **decreases**.

Section 17-5 Integrated Circuit Voltage Regulators

20. (a) 7806: **+6 V**
(b) 7905: **–5.2 V**
(c) 7818: **+18 V**
(d) 7924: **–24 V**

21. $V_{\text{OUT}} = \left(1 + \dfrac{R_2}{R_1}\right)V_{\text{REF}} + I_{\text{ADJ}}R_2 = \left(1 + \dfrac{10\text{ k}\Omega}{1.0\text{ k}\Omega}\right)1.25\text{ V} + (50\ \mu\text{A})(10\text{ k}\Omega)$

$= 13.7\text{ V} + 0.5\text{ V} = \mathbf{14.3\,V}$

22. $$V_{\text{OUT(min)}} = -\left[\left(1+\frac{R_{2(min)}}{R_1}\right)V_{\text{REF}} + I_{\text{ADJ}}R_{2(min)}\right]$$

$$R_{2(min)} = 0\ \Omega$$

$$V_{\text{OUT}(min)} = -(1.25\text{ V}(1+0)+0) = \mathbf{-1.25\ V}$$

$$V_{\text{OUT(max)}} = -\left[\left(1+\frac{R_{2(max)}}{R_1}\right)V_{\text{REF}} + I_{\text{ADJ}}R_{2(max)}\right] = -\left[1.25\text{ V}\left(1+\frac{10\text{ k}\Omega}{470\ \Omega}\right)+(50\ \mu\text{A})(10\text{ k}\Omega)\right]$$
$$= -\left(1.25\text{ V}(22.28)+0.5\text{ V}\right) = \mathbf{-28.4\ V}$$

23. The regulator current equals the current through $R_1 + R_2$.

$$I_{\text{REG}} \cong \frac{V_{\text{OUT}}}{R_1+R_2} = \frac{14.3\text{ V}}{11\text{ k}\Omega} = \mathbf{1.3\ mA}$$

24. $$V_{\text{IN}} = 18\text{ V},\ V_{\text{OUT}} = 12\text{ V}$$

$$I_{\text{REG(max)}} = 2\text{ mA},\quad V_{\text{REF}} = 1.25\text{ V}$$

$$R_1 = \frac{V_{\text{REF}}}{I_{\text{REG}}} = \frac{1.25\text{ V}}{2\text{ mA}} = \mathbf{625\ \Omega}$$

Neglecting I_{ADJ}:

$$V_{\text{R2}} = 12\text{ V} - 1.25\text{ V} = 10.8\text{ V}$$

$$R_2 = \frac{V_{\text{R2}}}{I_{\text{REG}}} = \frac{10.8\text{ V}}{2\text{ mA}} = \mathbf{5.4\ k\Omega}$$

For R_1 use **620 Ω** and for R_2 use either **5600 Ω** or a 10 kΩ potentiometer for precise adjustment to 12 V.

Section 17-6 Integrated Circuit Voltage Regulator Configurations

25. $$V_{Rext\text{(min)}} = 0.7\text{ V}$$

$$R_{\text{ext}} = \frac{0.7\text{ V}}{I_{\text{max}}} = \frac{0.7\text{ V}}{250\text{ mA}} = \mathbf{2.8\ \Omega}$$

26. $$V_{\text{OUT}} = +12\text{ V}$$

$$I_{\text{L}} = \frac{12\text{ V}}{10\ \Omega} = 1200\text{ mA} = 1.2\text{ A}$$

$$I_{\text{ext}} = I_{\text{L}} - I_{\text{max}} = 1.2\text{ A} - 0.5\text{ A} = 0.7\text{ A}$$

$$P_{\text{ext}} = I_{\text{ext}}(V_{\text{IN}} - V_{\text{OUT}}) = 0.7\text{ A}(15\text{ V} - 12\text{ V}) = 0.7\text{ A}(3\text{ V}) = \mathbf{2.1\ W}$$

27. $V_{Rlim(min)} = 0.7\text{ V}$

$$R_{lim(min)} = \frac{0.7\text{ V}}{I_{\text{ext}}} = \frac{0.7\text{ V}}{2\text{ A}} = \mathbf{0.35\ \Omega}$$

See Figure 17-2.

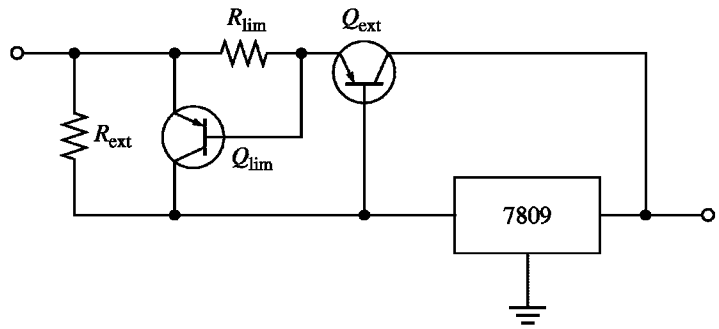

Figure 17-2

28. $R = \dfrac{1.25\text{ V}}{500\text{ mA}} = \mathbf{2.5\ \Omega}$

See Figure 17-3.

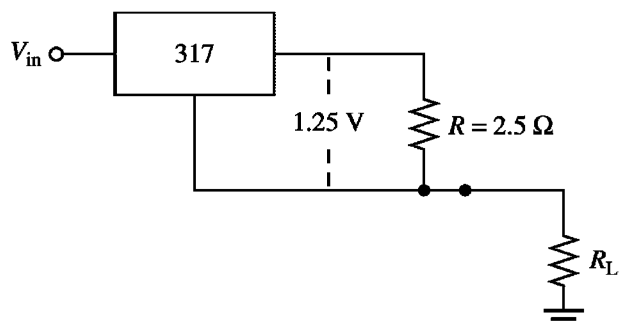

Figure 17-3

29. $I = 500\text{ mA}$

$$R = \frac{8\text{ V}}{500\text{ mA}} = \mathbf{16\ \Omega}$$

See Figure 17-4.

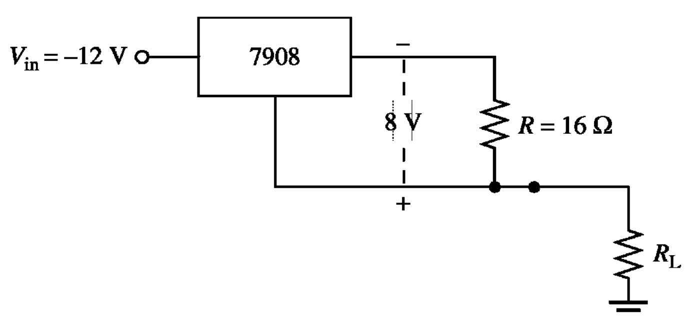

Figure 17-4

30. Connect pin 7 to pin 6.

Chapter 17

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 31 through 34 are available from the Instructor Resource Center. See Chapter 2 for instructions. The faults in the circuit files may be accessed using the password *book* (all lowercase).

31. R_2 leaky

32. Zener diode open

33. Q_2 collector-to-emitter open

34. R_1 open

Chapter 18
Communication Devices and Methods

Section 18-1 Basic Receivers

1. See Figure 18-1.

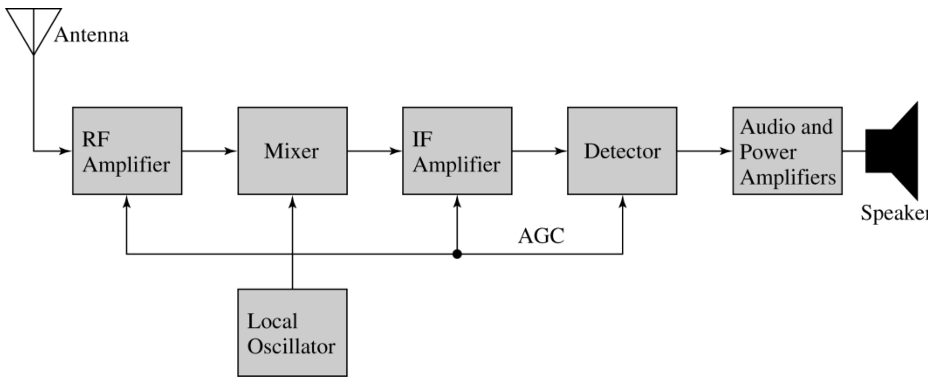

Figure 18-1

2. See Figure 18-2.

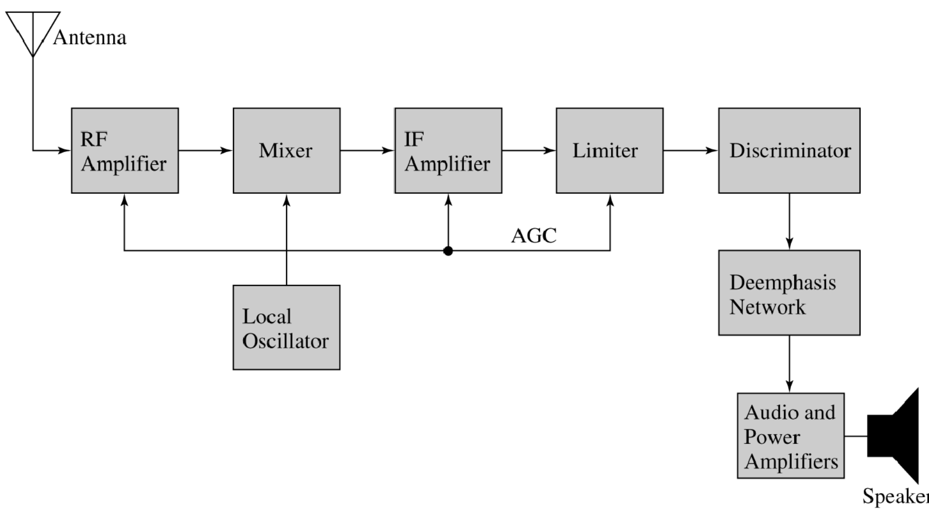

Figure 18-2

3. $f_{LO} = 680\text{ kHz} + 455\text{ kHz} = \mathbf{1135\,kHz}$

4. $f_{LO} = 97.2\text{ MHz} + 10.7\text{ MHz} = \mathbf{107.9\,MHz}$

5. $f_{\text{RF}} = 101.9\text{ MHz} - 10.7\text{ MHz} = \mathbf{91.2\ MHz}$

$f_{\text{IF}} = \mathbf{10.7\ MHz}$ (always)

Section 18-2 The Linear Multiplier

6. (a) $V_{out} \cong \mathbf{-2.5\ V}$

(b) $V_{out} \cong \mathbf{-1.6\ V}$

(c) $V_{out} \cong \mathbf{+1.0\ V}$

(d) $V_{out} \cong \mathbf{+10\ V}$

7. $V_{out} = KV_XV_Y = 0.125(+3.5\text{ V})(-2.9\text{ V}) = \mathbf{-1.27\ V}$

8. Connect the two inputs together.

9. (a) $V_{out} = KV_1V_2 = (0.1)(+2\text{ V})(+1.4\text{ V}) = \mathbf{+0.28\ V}$

(b) $V_{out} = KV_1V_2 = KV_1^2(0.1)(-3.2\text{ V})^2 = \mathbf{+1.024\ V}$

(c) $V_{out} = \dfrac{-V_1}{V_2} = \dfrac{-(6.2\text{ V})}{-3\text{ V}} = \mathbf{+2.07\ V}$

(d) $V_{out} = \sqrt{V_1} = \sqrt{6.2\text{ V}} = \mathbf{+2.49\ V}$

Section 18-3 Amplitude Modulation

10. $f_{diff} = f_1 - f_2 = 100\text{ kHz} - 30\text{ kHz} = \mathbf{70\ kHz}$

$f_{sum} = f_1 + f_2 = 100\text{ kHz} + 30\text{ kHz} = \mathbf{130\ kHz}$

11. $f_1 = \dfrac{9\text{ cycles}}{1\text{ ms}} = 9000\text{ cycles/s} = 9\text{ kHz}$

$f_2 = \dfrac{1\text{ cycles}}{1\text{ ms}} = 1000\text{ cycles/s} = 1\text{ kHz}$

$f_{diff} = f_1 - f_2 = 9\text{ kHz} - 1\text{ kHz} = \mathbf{8\ kHz}$

$f_{sum} = f_1 + f_2 = 9\text{ kHz} + 1\text{ kHz} = \mathbf{10\ kHz}$

12. $f_c = 1000\text{ kHz}$

$f_{diff} = 1000\text{ kHz} - 3\text{ kHz} = \mathbf{997\ kHz}$

$f_{sum} = 1000\text{ kHz} + 3\text{ kHz} = \mathbf{1003\ kHz}$

13. $f_1 = \dfrac{18 \text{ cycles}}{10\ \mu\text{s}} = 1.8 \text{ MHz}$

$f_2 = \dfrac{1 \text{ cycles}}{10\ \mu\text{s}} = 100 \text{ kHz}$

$f_{diff} = f_1 - f_2 = 1.8 \text{ MHz} - 100 \text{ kHz} = \mathbf{1.7\ MHz}$

$f_{sum} = f_1 + f_2 = 1.8 \text{ MHz} + 100 \text{ kHz} = \mathbf{1.9\ MHz}$

$f_c = \mathbf{1.8\ MHz}$

14. $f_c = 1.2 \text{ MHz}$ by inspection

$f_m = f_c - f_{diff} = 1.2 \text{ MHz} - 1.1955 \text{ MHz} = \mathbf{4.5\ kHz}$

15. $f_c = \dfrac{f_{diff} + f_{sum}}{2} = \dfrac{847 \text{ kHz} + 853 \text{ KHz}}{2} = \mathbf{850\ kHz}$

$f_m = f_c - f_{diff} = 850 \text{ kHz} - 847 \text{ kHz} = \mathbf{3\ kHz}$

16. $f_{diff(min)} = 600 \text{ kHz} - 3 \text{ kHz} = \mathbf{597\ kHz}$

$f_{diff(max)} = 600 \text{ kHz} - 300 \text{ Hz} = \mathbf{599.7\ kHz}$

$f_{sum(min)} = 600 \text{ kHz} + 300 \text{ kHz} = \mathbf{600.3\ kHz}$

$f_{sum(max)} = 600 \text{ kHz} + 3 \text{ kHz} = \mathbf{603\ kHz}$

See Figure 18-3.

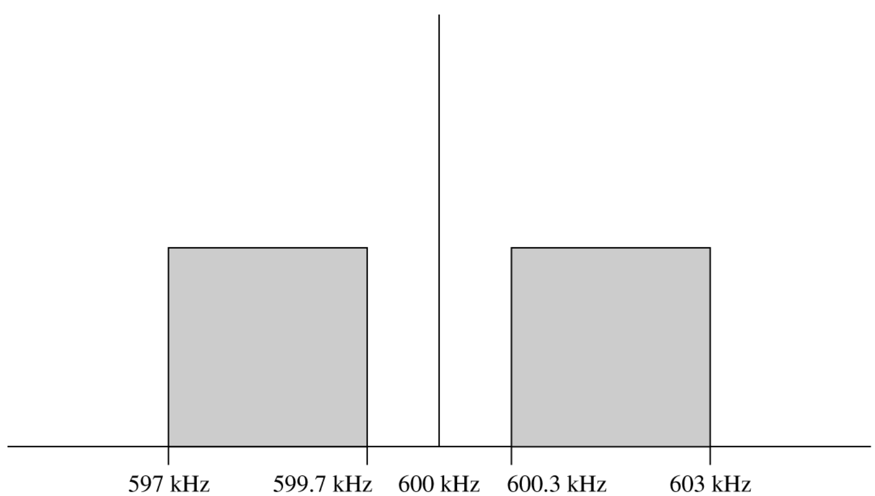

Figure 18-3

Section 18-4 The Mixer

17. $(\sin A)(\sin B) = \frac{1}{2}[\cos(A - B) - \cos(A + B)]$

$V_{in(1)} = 0.2\ \text{V} \sin [2\pi(2200\ \text{kHz})t]$

$V_{in(2)} = 0.15\ \text{V} \sin [2\pi(3300\ \text{kHz})t]$

$V_{in(1)}V_{in(2)} = (0.2\ \text{V})(0.15\ \text{V}) \sin [2\pi(2200\ \text{kHz})t] \sin [2\pi(3300\ \text{kHz})t]$

$V_{out} = \frac{(0.2\ \text{V})(0.15\ \text{V})}{2}[\cos 2\pi(3300\ \text{kHz} - 2200\ \text{kHz})t - \cos 2\pi(3300\ \text{kHz} + 2200\ \text{kHz})t]$

$V_{out} = 15\ \text{mV} \cos [2\pi(1100\ \text{kHz})t] - 15\ \text{mV} \cos [2\pi(5500\ \text{kHz})t]$

18. $f_{\text{IF}} = f_{\text{LO}} - f_c = 986.4\ \text{kHz} - 980\ \text{kHz} = \mathbf{6.4\ kHz}$

Section 18-5 AM Demodulation

19. See Figure 18-4.

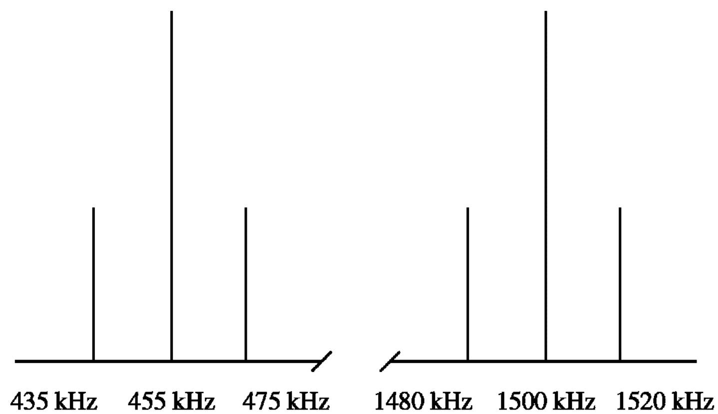

Figure 18-4

20. See Figure 18-5.

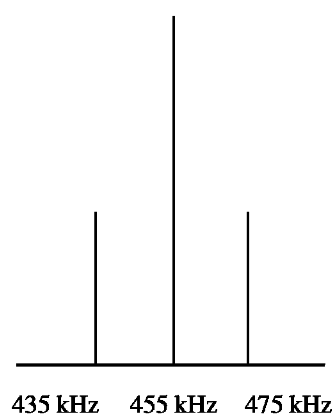

Figure 18-5

21. See Figure 18-6.

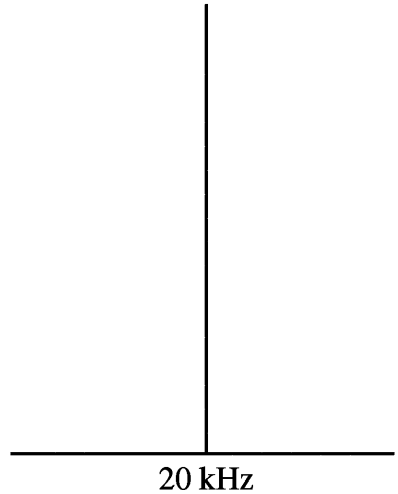

Figure 18-6

Section 18-6 IF and Audio Amplifiers

22. $f_c - f_m = 1.2\text{ MHz} - 8.5\text{ kHz} = 1.1915\text{ MHz}$

$f_c + f_m = 1.2\text{ MHz} + 8.5\text{ kHz} = 1.2085\text{ MHz}$

$f_c = 1.2\text{ MHz}$

$f_{\text{LO}} - f_m = 455\text{ kHz} - 8.5\text{ kHz} = 446.5\text{ kHz}$

$f_{\text{LO}} + f_m = 455\text{ kHz} + 8.5\text{ kHz} = 463.5\text{ kHz}$

$f_{\text{LO}} = 455\text{ kHz}$

23. The **IF amplifier** has a 450 kHz to 460 kHz passband.

The **audio/power amplifiers** have a 10 Hz to 5 kHz bandpass.

Section 18-7 Frequency Modulation

24. An FM signal differs from an AM signal in that the information is contained in frequency variations of the carrier rather than amplitude variations.

25. Varactor

Chapter 18

Section 18-8 The Phase-Locked Loop (PLL)

26. See Figure 18-7.

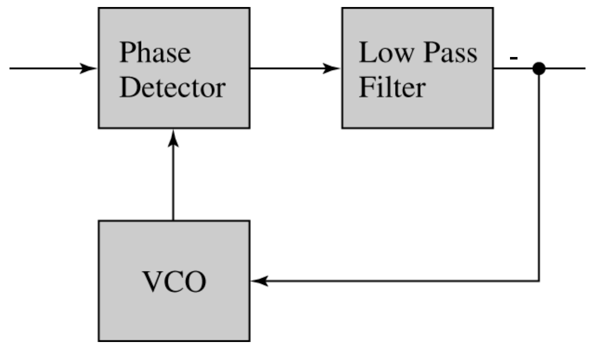

Figure 18-7

27. (a) The VCO signal is locked onto the incoming signal and therefore its frequency is equal to the incoming frequency of **10 MHz**.

(b) $V_c = \dfrac{V_i V_o}{2}\cos\theta_e \dfrac{(250\text{ mA})(400\text{ mV})}{2}\cos(30° - 15°) = (0.050)(0.966) = \mathbf{48.3\ mV}$

28. $\Delta f_o = +3.6\text{ kHz},\qquad \Delta V_c = +0.5\text{ V}$

$$K = \frac{\Delta f_o}{\Delta V_c} = \frac{+3.6\text{ kHz}}{+0.5\text{ V}} = \mathbf{7.2\ kHz/V}$$

29. $K = 1.5\text{ kHz/V},\qquad \Delta V_c = +0.67\text{ V}$

$$K = \frac{\Delta f_o}{\Delta V_c}$$

$$\Delta f_o = K\Delta V_c = (1.5\text{ kHz/V})(+0.67\text{ V}) = \mathbf{1005\ Hz}$$

Section 18-9 Fiber Optics

30. The light ray will be **reflected** because the angle of incidence (30°) is greater than the critical angle (15°).

31. $\theta_C = \cos^{-1}(n_2/n_1) = \cos^{-1}(1.25/1.55) = \mathbf{36.2°}$