Chapter 1
Introduction to Electronics

Section 1-1 Atomic Structure

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

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

Section 1-2 Materials Used in Electronics

3. The materials represented in Figure 1−21 in the textbook are
(a) insulator (b) semiconductor (c) conductor

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

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

Section 1-3 Current in Semiconductors

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

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

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

8. 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).

9. 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

10. 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.

11. 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
Diode 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.

Section 2-2 Voltage-Current Characteristic of a Diode

3. 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.

4. 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

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

6. (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) $V_F = \mathbf{0.7\ V}$

7. (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) $V_F = \mathbf{0\ V}$

8. 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

9. See Figure 2-1.

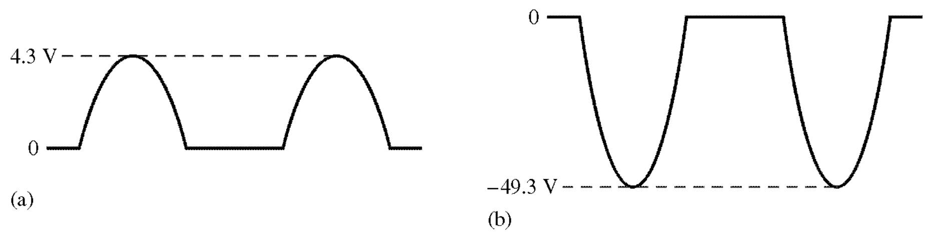


Figure 2-1

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

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

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

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

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

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

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

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

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

Chapter 2

Section 2-5 Full-Wave Rectifiers

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

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

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

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

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

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

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

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

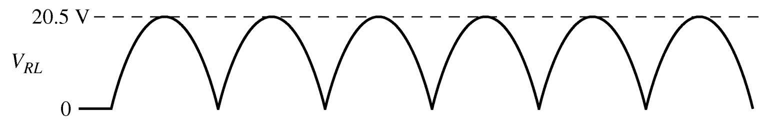


Figure 2-2

(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) PIV = 21.2 V + 20.5 V = **41.7 V**

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

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

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

18. See Figure 2-3.

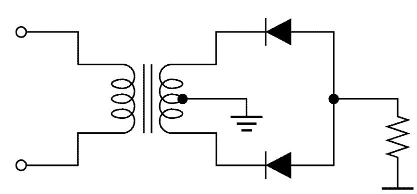


Figure 2-3

19. PIV $= V_p = \dfrac{\pi V_{AVG(out)}}{2} = \dfrac{\pi(50\text{ V})}{2}$ $=$ **78.5 V**

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

21. See Figure 2-4.

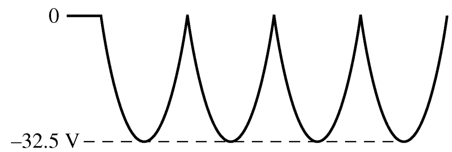


Figure 2-4

Section 2-6 Power Supply Filters and Regulators

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

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

23. $V_{r(pp)} = \dfrac{V_{p(in)}}{fR_LC} = \dfrac{30\text{ V}}{(120\text{ Hz})(600\,\Omega)(50\ \mu\text{F})}$ $=$ **8.33 V pp**

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

24. $\%r = \left(\dfrac{V_{r(pp)}}{V_{DC}}\right)100 = \left(\dfrac{8.33\text{ V}}{25.8\text{ V}}\right)100$ $=$ **32.3%**

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

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

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

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

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

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

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

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

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

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

28. $V_{p(sec)} = 1.414(36\text{ V}) = 50.9\text{ V}$
See Figure 2-5.

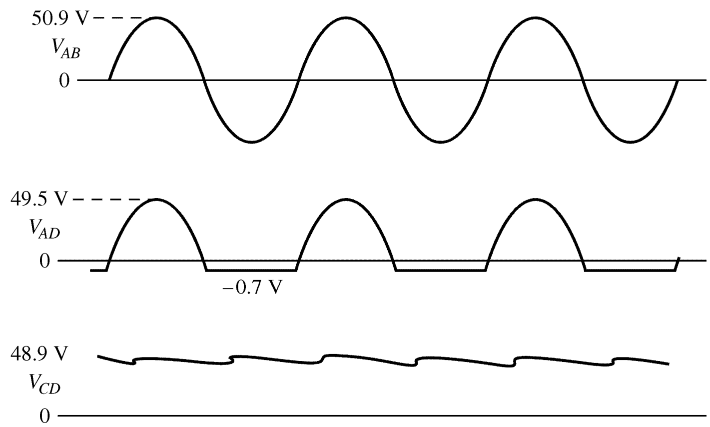


Figure 2-5

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

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

Section 2-7 Diode Limiters and Clampers

31. See Figure 2-6.

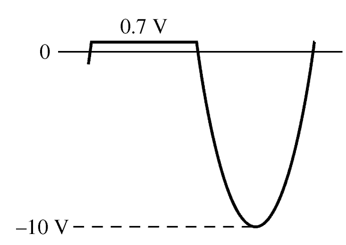


Figure 2-6

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

(b) $25\text{ V} = V_{R1} + V_{R2} + 0.7\text{ V}$
$2V_R = 24.3\text{ V}$
$V_R = \dfrac{24.3\text{ V}}{2} = 12.15\text{ V}$
$V_{out} = V_R + 0.7\text{ V} = 12.15\text{ V} + 0.7\text{ V} = 12.85\text{ V}$
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).

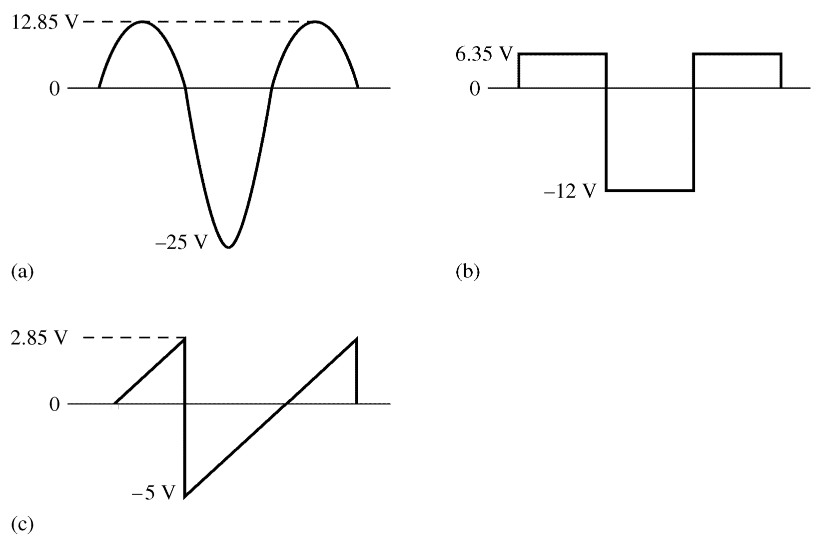


Figure 2-7

33. See Figure 2-8.

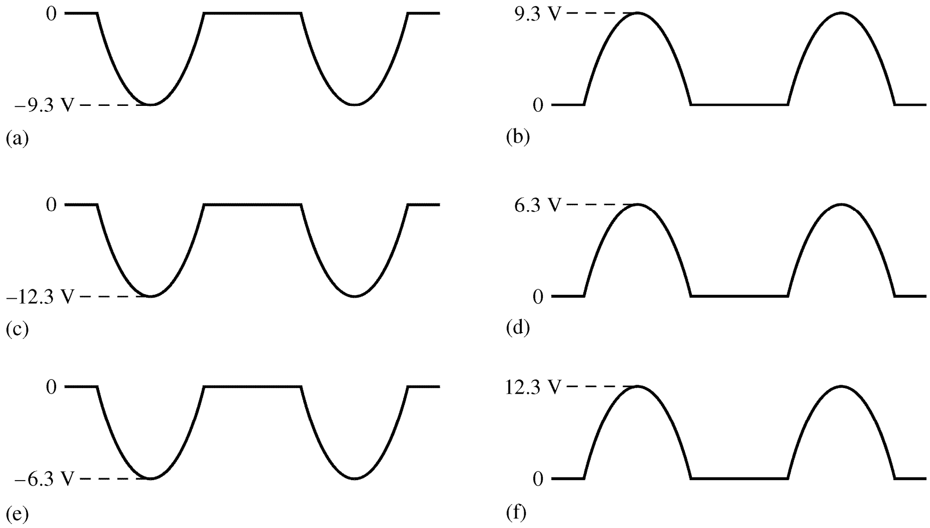


Figure 2-8

34. See Figure 2-9.

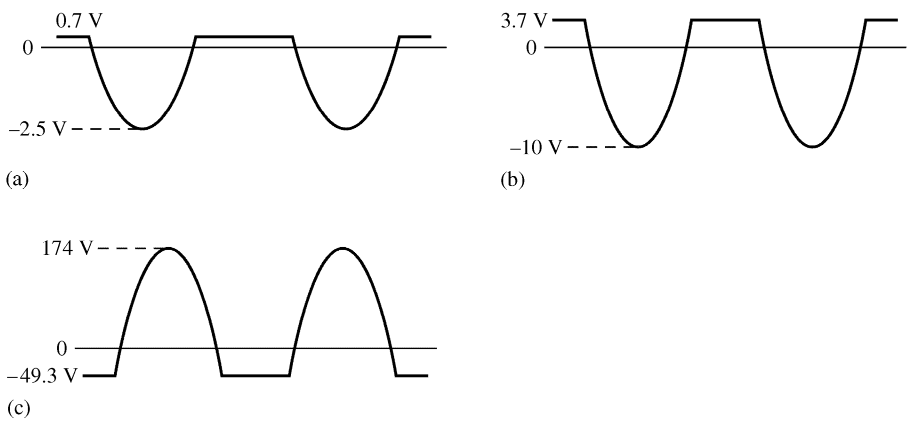


Figure 2-9

35. See Figure 2-10.

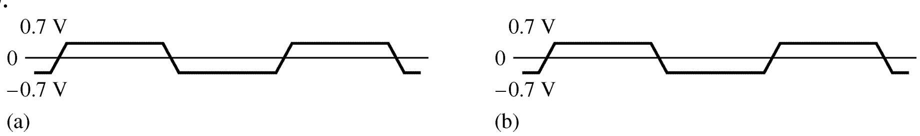


Figure 2-10

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

(b) Same as (a).

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

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

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

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

38. See Figure 2-11.

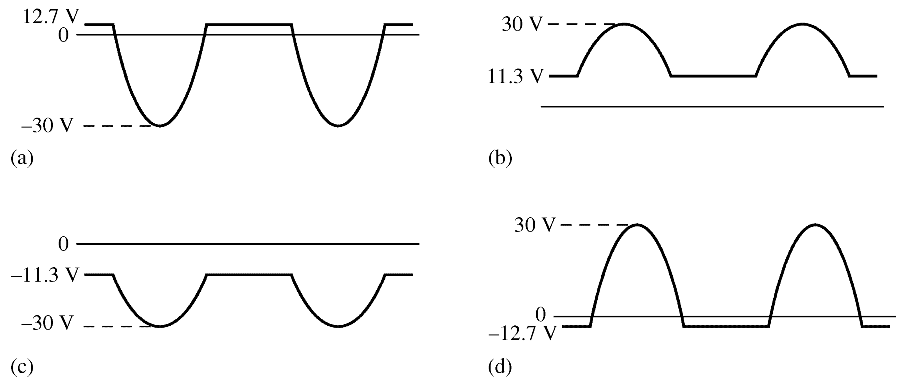


Figure 2-11

39. (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.

40. (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

41. $V_{\text{OUT}} = 2V_{p(in)} = 2(1.414)(20\text{ V}) =$ **56.6 V**
See Figure 2-12.

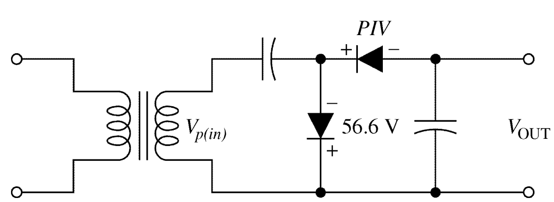


Figure 2-12

42. $V_{OUT(trip)} = 3V_{p(in)} = 3(1.414)(20\text{ V}) = \mathbf{84.8\ V}$
$V_{OUT(quad)} = 4V_{p(in)} = 4(1.414)(20\text{ V}) = \mathbf{113\ V}$
See Figure 2-13.

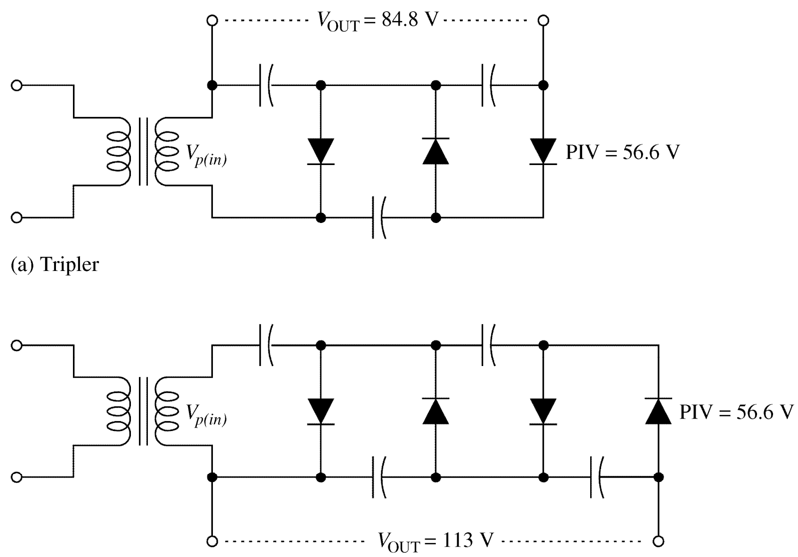


Figure 2-13

Section 2-9 The Diode Datasheet

43. The PIV is specified as the peak repetitive reverse voltage = **100 V**.

44. The PIV is specified as the peak repetitive reverse voltage = **1000 V**.

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

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

Section 2-10 Troubleshooting

46. (a) Since $V_D = 25\text{ V} = 0.5V_S$, the diode is **open**.
(b) The diode is forward-biased but since $V_D = 15\text{ V} = V_S$, the diode is **open.**
(c) The diode is reverse-biased but since $V_R = 2.5\text{ V} = 0.5V_S$, the diode is **shorted**.
(d) The diode is reverse-biased and $V_R = 0\text{ V}$. The diode is **operating properly.**

47. $V_A = V_{S1} = \mathbf{+25\ V}$
$V_B = V_{S1} - 0.7\text{ V} = 25\text{ V} - 0.7\text{ V} = \mathbf{+24.3\ V}$
$V_C = V_{S2} + 0.7\text{ V} = 8\text{ V} + 0.7\text{ V} = \mathbf{+8.7\ V}$
$V_D = V_{S2} = \mathbf{+8.0\ V}$

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

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

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.**

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

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

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

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 PIV = 2(17 V) + 0.7 V = 34.7 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.

Application Activity Problems

52. (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.

53. The rectifier must be connected backwards.

54. −16 V with 60 Hz ripple

Advanced Problems

55. $V_r = \left(\frac{1}{fR_LC}\right)V_{p(in)}$

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

56. $V_{\text{DC}} = \left(1 - \dfrac{1}{2fR_LC}\right)V_{p(in)}$

$$\frac{V_{\text{DC}}}{V_{p(in)}} = \left(1 - \frac{1}{2fR_LC}\right)$$

$$\frac{1}{2fR_LC} = 1 - \frac{V_{\text{DC}}}{V_{p(in)}}$$

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

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

Then

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

57. The capacitor input voltage is

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

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

The nearest standard value is 680 mΩ.

58. 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,

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

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

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

The nearest standard value is 270 μF.

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

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

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

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

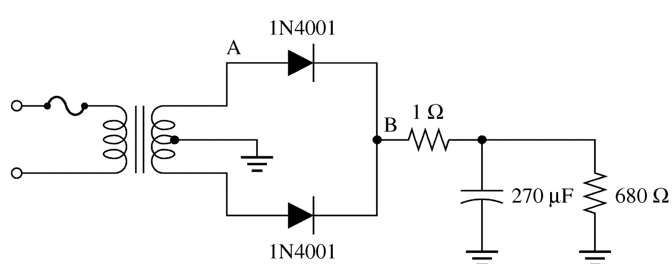


Figure 2-14

59. See Figure 2-15.

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

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

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

$V_r = 2(0.35\text{ V}) = 0.71$ 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 $C = 1200\ \mu$F.

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

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

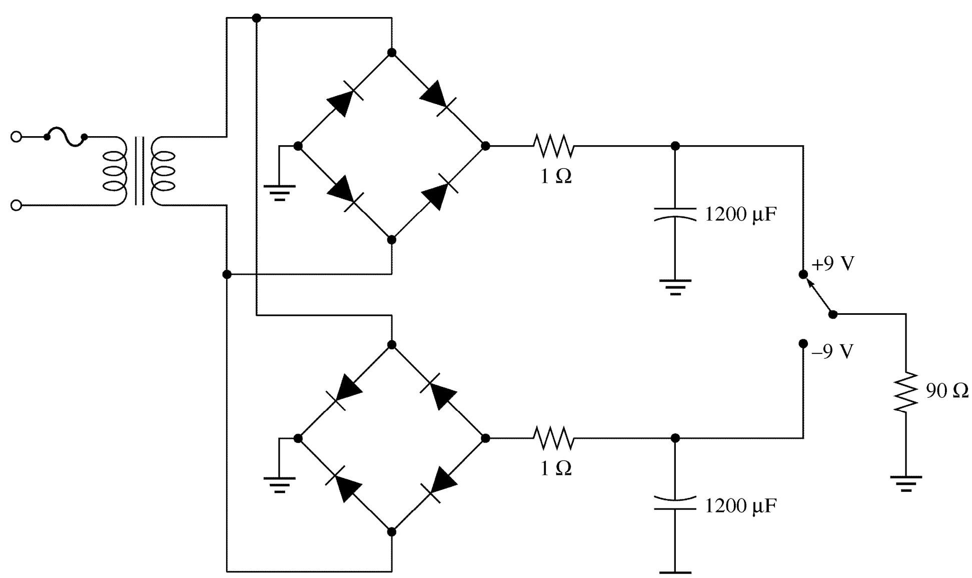


Figure 2-15

60. See Figure 2-16.

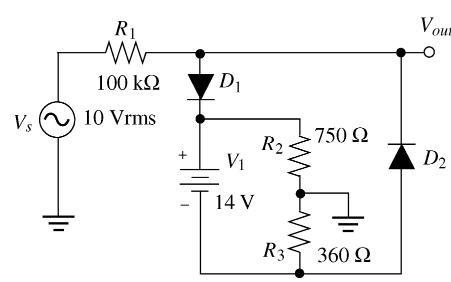


Figure 2-16

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

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

Chapter 2

MultiSim Troubleshooting Problems

The solutions showing instrument connections for Problems 62 through 79 are available from the Instructor Resource Center. The faults in the circuit files may be accessed using the password *book* (all lowercase).

To access supplementary materials online, instructors need to request an instructor access code. Go to www.pearsonhighered.com/irc to register for an instructor access code. Within 48 hours of registering, you will receive a confirming e-mail including an instructor access code. Once you have received your code, locate your text in the online catalog and click on the Instructor Resources button on the left side of the catalog product page. Select a supplement, and a login page will appear. Once you have logged in, you can access instructor material for all Prentice Hall textbooks. If you have any difficulties accessing the site or downloading a supplement, please contact Customer Service at http://247.prenhall.com.

62. Diode shorted

63. Diode open

64. Diode open

65. Diode shorted

66. No fault

67. Diode shorted

68. Diode leaky

69. Diode open

70. Diode shorted

71. Diode shorted

72. Diode leaky

73. Diode open

74. Bottom diode open

75. Reduced transformer turns ratio

76. Open filter capacitor

77. Diode leaky

78. D_1 open

79. Load resistor open

Chapter 3
Special-Purpose Diodes

Section 3-1 The Zener Diode

1. See Figure 3-1.

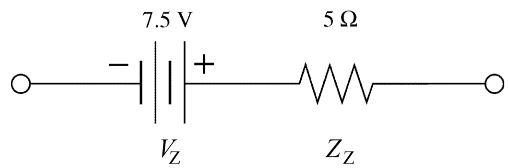


Figure 3-1

2. $I_{ZK} \cong$ **3 mA**
$V_Z \cong$ **−9 V**

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

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. $\Delta T = 70°\text{C} - 25°\text{C} = 45°\text{C}$
$V_Z = 6.8\text{ V} + \dfrac{(6.8\text{ V})(0.0004/°\text{C})}{45°\text{C}} = 6.8\text{ C} + 0.12\text{ V} = \mathbf{6.92\ V}$

Section 3-2 Zener Diode Applications

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

7. $\Delta V_Z = (I_Z - I_{ZK})Z_Z = (28.5\text{ mA})(20\ \Omega) = 0.57\text{ V}$
$V_{OUT} = V_Z - \Delta V_Z = 14\text{ V} - 0.57\text{ V} = 13.43\text{ V}$
$V_{IN(min)} = I_{ZK}R + V_{OUT} = (1.5\text{ mA})(560\ \Omega) + 13.43\text{ V} = \mathbf{14.3\ V}$

8. $\Delta V_Z = I_Z Z_Z = (40\text{ mA} - 30\text{ mA})(30\ \Omega) = 0.3\text{ V}$
$V_Z = 12\text{ V} + \Delta V_Z = 12\text{ V} + 0.3\text{ V} = 12.3\text{ V}$
$R = \dfrac{V_{IN} - V_Z}{40\text{ mA}} = \dfrac{18\text{ V} - 12.3\text{ V}}{40\text{ mA}} = \mathbf{143\ \Omega}$

Chapter 3

9. $V_Z \cong 12\text{ V} + 0.3\text{ V} = 12.3\text{ V}$
See Figure 3-2.

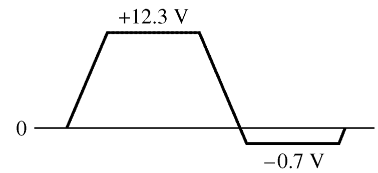


Figure 3-2

10. $V_{Z(min)} = V_Z - \Delta I_Z Z_Z = 5.1\text{ V} - (49\text{ mA} - 1\text{ mA})(7\ \Omega)$
$= 5.1\text{ V} - (48\text{ mA})(7\ \Omega) = 5.1\text{ V} - 0.336\text{ V} = 4.76\text{ V}$
$V_R = 8\text{ V} - 4.76\text{ V} = 3.24\text{ V}$

$$I_T = \frac{V_R}{R} = \frac{3.24\text{ V}}{22\ \Omega} = 147\text{ mA}$$

$I_{L(max)} = 147\text{ mA} - 1\text{ mA} =$ **146 mA**
$V_{Z(max)} = 5.1\text{ V} + (70\text{ mA} - 49\text{ mA})(7\ \Omega) = 5.1\text{ V} + 147\text{ mV} = 5.25\text{ V}$
$V_R = 8\text{ V} - 5.25\text{ V} = 2.75\text{ V}$

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

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

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

12. 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:

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

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

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

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

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

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

Section 3-3 The Varactor Diode

16. At 5 V, C = 20 pF
At 20 V, C = 10 pF
ΔC = 20 pF − 10 pF = **10 pF** (decrease)

17. From the graph, V_R = **3 V** @ 25 pF

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

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

Since they are in series, each varactor must have a capacitance of $2C_T$ = **25.4 pF**

19. 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

20. $$I_F = \frac{24\text{ V}}{680\ \Omega} = 35.3\text{ mA}$$

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

21. See Figure 3-3.

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

The nearest standard 1% value is 97.6 Ω or the nearest standard 5% value is 91 Ω.

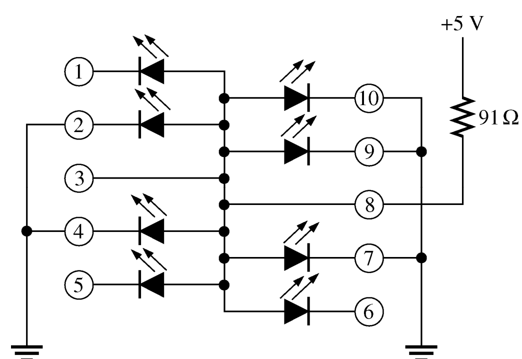


Figure 3-3

22. $V_F \cong 2.2$ V for $I_F = 20$ mA

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

Select 3 LEDs/branch:

$$\text{Number of branches} = \frac{48}{3} = 16$$

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

Use sixteen 120 Ω resistors.

23. $V_F \cong 2.5$ V for $I_F = 30$ mA

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

Select 5 LEDs/branch:

$$\text{Number of branches} = \frac{100}{5} = 20$$

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

See Figure 3-4.

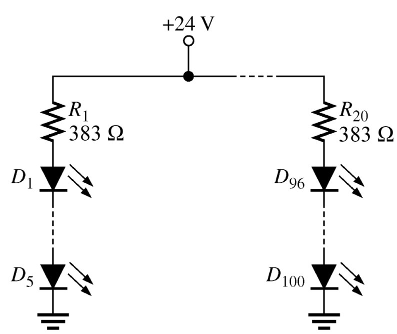


Figure 3-4

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

25. (a) $R = \frac{V_S}{I} = \frac{3\text{ V}}{100\ \mu\text{A}}$ = **30 kΩ**

(b) $R = \frac{V_S}{I} = \frac{3\text{ V}}{350\ \mu\text{A}}$ = **8.57 kΩ**

(c) $R = \frac{V_S}{I} = \frac{3\text{ V}}{510\ \mu\text{A}}$ = **5.88 kΩ**

26. The microammeter reading will increase.

Section 3-5 Other Types of Diodes

27. $R = \frac{\Delta V}{\Delta I} = \frac{125\text{ mV} - 200\text{ mV}}{0.25\text{ mA} - 0.15\text{ mA}} = \frac{-75\text{ mV}}{0.10\text{ mA}}$ = **−750 Ω**

28. Tunnel diodes are used in oscillators.

29. 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 3-6 Troubleshooting

30. (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.

31. (a) With D_5 open, $V_{OUT} \cong$ **30 V**.
(b) With R open, V_{OUT} = **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_{OUT} = **0 V**.
(h) With F open, V_{OUT} = **0 V**.

Application Activity Problems

32. (a) Faulty regulator

33. Incorrect transformer secondary voltage

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

35. $I_L = \frac{12\text{ V}}{1\text{ k}\Omega}$ = 12 mA; V_{reg} = 16 V − 12 V = 4 V
P_{reg} = (4 V)(12 mA) = **48 mW**

Chapter 3

Datasheet Problems

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

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

(b) For a 1N4751A:

@ 70°C; $P_{D(max)}$ = 1.0 W − (6.67 mW/°C)(20°C) = 1.0 W − 133 mW = **867 mW**

@ 100°C; $P_{D(max)}$ = 1.0 W − (6.67 mW/°C)(50°C) = 1.0 W − 333 mW = **667 mW**

(c) I_{ZK} = **0.5 mA** for a 1N4738A

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

(e) ΔZ_Z = 700 Ω − 7.0 Ω = **693 Ω** for a 1N4740A

37. From the datasheet of textbook Figure 3-24:

(a) $I_{F(max)}$ = **200 mA**

(b) C_{max} = 11 pF

(c) $C_{20} = \dfrac{C_2}{CR} = \dfrac{100\text{ pF}}{6.5}$ = 15.4 pF; range is 100 pF − 15.4 pF for an 836A.

38. From the datasheet of textbook 3-34:

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

(b) When 5.1 V is used to forward-bias the TSMF1000 for I_F = 20 mA, $V_F \cong$ 1.3 V

$R = \dfrac{5.1\text{ V} - 1.3\text{ V}}{20\text{ mA}} = \dfrac{3.8\text{ V}}{20\text{ mA}}$ = **190 Ω**

(c) At 25°C maximum power dissipation is 190 mW.

If V_F = 1.5 V and I_F = 50 mA, P_D = 75 mW. The power rating is **not exceeded.**

(d) For I_F = 40 mA, radiant intensity is approximately **0.9 mW/sr**.

(e) For I_F = 100 mA and θ = 20°, radiant intensity is 40% of maximum or (0.4)(25 mW/sr) = **10 mW/sr**

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

(a) With no incident light and a 10 kΩ series resistor, the typical voltage across the resistor is approximately V_R = (1 nA)(1 kΩ) = **1 μV**.

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

(c) Sensitivity is maximum for $\lambda \cong$ **830 nm**.

Advanced Problems

40. See Figure 3-5.

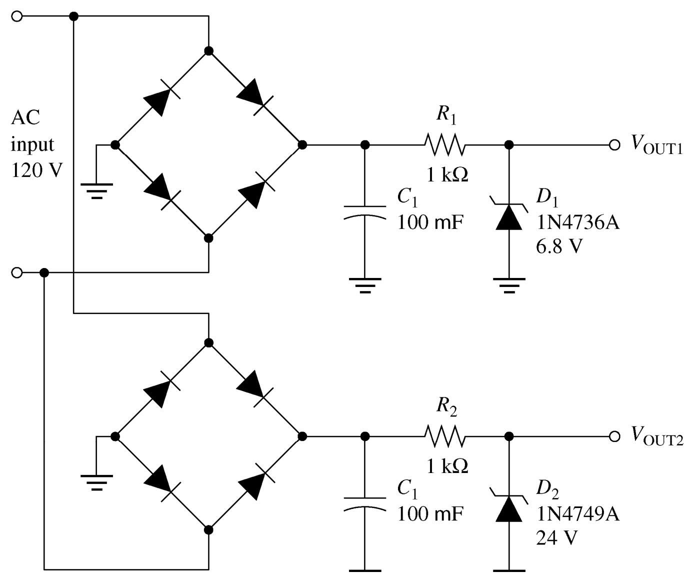


Figure 3-5

41. $V_{OUT(1)} \cong$ **6.8 V**, $V_{OUT(2)} \cong$ **24 V**

42. For a 10 kΩ load on each output:

$$I_{OUT(1)} = \frac{V_{OUT1}}{R_1} \cong \frac{6.8\text{ V}}{10\text{ k}\Omega} = 0.68\text{ mA}$$

$$I_{OUT(2)} = \frac{V_{OUT2}}{R_2} \cong \frac{24\text{ V}}{10\text{ k}\Omega} = 2.4\text{ mA}$$

$$V_{R1} \cong 120\text{ V} - 6.8\text{ V} = 113.2\text{ V}$$

$$I_{Z1} = \frac{113.2\text{ V}}{1\text{ k}\Omega} - 0.68\text{ mA} = 112.5\text{ mA}$$

$$V_{R2} \cong 120\text{ V} - 24\text{ V} = 96\text{ V}$$

$$I_{Z2} = \frac{96\text{ V}}{1\text{ k}\Omega} - 2.4\text{ mA} = 93.6\text{ mA}$$

I_T = 0.68 mA + 2.4 mA + 112.5 mA + 93.6 mA = 209.2 mA

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

43. See Figure 3-6.

Use a 1N4738A zener.

I_T = 35 mA + 31 mA = 66 mA

$$R = \frac{24\text{ V} - 8.2\text{ V}}{66\text{ mA}} = 239\ \Omega$$

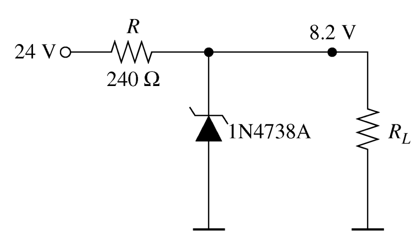


Figure 3-6

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

$C_{\min} = \dfrac{1}{4\pi^2 L f_{\max}^2} = \dfrac{1}{4\pi^2 (2\text{ mH})(850\text{ kHz})^2} = 17.5\text{ pF}$

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

45. See Figure 3-7. From datasheet, $V_F = 2.1$ V for red LED.

$R = \dfrac{V_D}{I} = \dfrac{12\text{ V} - 2.1\text{ V}}{20\text{ mA}} = 495\ \Omega$

Use standard value of 510 Ω.

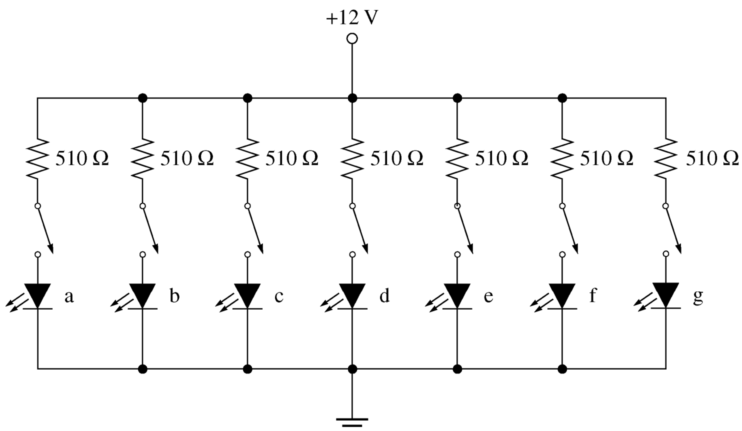


Figure 3-7

46. See Figure 3-8.

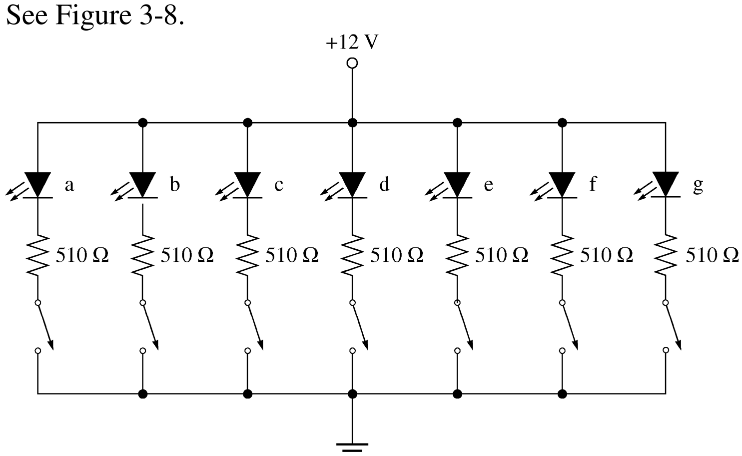


Figure 3-8

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 47 through 50 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).

47. Zener diode open

48. Capacitor open

49. Zener diode shorted

50. Resistor open

Chapter 4
Bipolar Junction Transistors

Section 4-1 Bipolar Junction Transistor (BJT) Structure

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

2. 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

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

4. $I_B = 0.02I_E = 0.02(30 \text{ mA}) = 0.6 \text{ mA}$
$I_C = I_E - I_B = 30 \text{ mA} - 0.6 \text{ mA} = \mathbf{29.4 \text{ mA}}$

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

6. $I_C = I_E - I_B = 5.34 \text{ mA} - 475\ \mu\text{A} = \mathbf{4.87 \text{ mA}}$

Section 4-3 BJT Characteristics and Parameters

7. $\alpha_{DC} = \dfrac{I_C}{I_E} = \dfrac{8.23 \text{ mA}}{8.69 \text{ mA}} = \mathbf{0.947}$

8. $\beta_{DC} = \dfrac{I_C}{I_B} = \dfrac{25 \text{ mA}}{200\ \mu\text{A}} = \mathbf{125}$

9. $I_B = I_E - I_C = 20.5 \text{ mA} - 20.3 \text{ mA} = 0.2 \text{ mA} = 200\ \mu\text{A}$
$\beta_{DC} = \dfrac{I_C}{I_B} = \dfrac{20.3 \text{ mA}}{200\ \mu\text{A}} = \mathbf{101.5}$

10. $I_E = I_C + I_B = 5.35 \text{ mA} + 50\ \mu\text{A} = 5.40 \text{ mA}$
$\alpha_{DC} = \dfrac{I_C}{I_E} = \dfrac{5.35 \text{ mA}}{5.40 \text{ mA}} = \mathbf{0.99}$

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

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

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

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

14. $I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3\text{ V} - 0.7\text{ V}}{100\text{ k}\Omega} = \mathbf{23\ \mu A}$

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

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

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

15. 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

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

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

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

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

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

$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{-3\text{ V} - (-0.7\text{ V})}{27\text{ k}\Omega} = \frac{-2.3\text{ V}}{27\text{ k}\Omega} = -85.2\ \mu\text{A}$

$I_C = \beta_{DC} I_B = 125(-85.2\ \mu\text{A}) = -10.7\text{ mA}$

$V_{CE} = V_{CC} - I_C R_C = -8\text{ V} - (-10.7\text{ mA})(390\ \Omega) = \mathbf{-3.83\ V}$

$V_{CB} = V_{CE} - V_{BE} = -3.83\text{ V} - (-0.7\text{ V}) = \mathbf{-3.13\ V}$

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

$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{3.9\text{ k}\Omega} = 1.1\text{ mA}$

$I_C = \beta_{DC} I_B = 50(1.1\text{ mA}) = 55\text{ mA}$

$I_C < I_{C(sat)}$

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

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

$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3\text{ V} - 0.7\text{ V}}{27\text{ k}\Omega} = 85.2\ \mu\text{A}$

$I_C = \beta_{DC} I_B = 125(85.2\ \mu\text{A}) = 10.7\text{ mA}$

$I_C < I_{C(sat)}$

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

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

$V_E = V_B - V_{BE} = 2\text{ V} - 0.7\text{ V} = 1.3\text{ V}$

$I_E = \frac{V_E}{R_E} = \frac{1.3\text{ V}}{1.0\text{ k}\Omega} = \mathbf{1.3\ mA}$

$I_C = \alpha_{DC} I_E = (0.98)(1.3\text{ mA}) = \mathbf{1.27\ mA}$

$\beta_{DC} = \frac{\alpha_{DC}}{1 - \alpha_{DC}} = \frac{0.98}{1 - 0.98} = 49$

$I_B = I_E - I_C = 1.3\text{ mA} - 1.27\text{ mA} = \mathbf{30\ \mu A}$

20. (a) $V_B = V_{BB} = \mathbf{10\ V}$

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

$V_E = V_B - V_{BE} = 10\text{ V} - 0.7\text{ V} = \mathbf{9.3\ V}$

$V_{CE} = V_C - V_E = 20\text{ V} - 9.3\text{ V} = \mathbf{10.7\ V}$

$V_{BE} = \mathbf{0.7\ V}$

$V_{CB} = V_C - V_B = 20\text{ V} - 10\text{ V} = \mathbf{10\ V}$

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

$V_C = V_{CC} = \mathbf{-12\ V}$

$V_E = V_B - V_{BE} = -4\text{ V} - (-0.7\text{ V}) = \mathbf{-3.3\ V}$

$V_{CE} = V_C - V_E = -12\text{ V} - (-3.3)\text{ V} = \mathbf{-8.7\ V}$

$V_{BE} = \mathbf{-0.7\ V}$

$V_{CB} = V_C - V_B = -12\text{ V} - (-4\text{ V}) = \mathbf{-8\ V}$

21. For $\beta_{DC} = 100$:

$I_E = \frac{V_B - V_{BE}}{R_E} = \frac{10\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = 930\ \mu\text{A}$

$\alpha_{DC} = \frac{\beta_{DC}}{1 + \beta_{DC}} = \frac{100}{101} = 0.990$

$I_C = \alpha_{DC} I_E = (0.990)(930\ \mu\text{A}) = 921\ \mu\text{A}$

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

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

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

Section 4-4 The BJT as an Amplifier

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

25. $$A_v = \frac{V_{out}}{V_{in}} = \frac{10\text{ V}}{300\text{ mV}} = \mathbf{33.3}$$

26. $$A_v = \frac{R_C}{r'_e} = \frac{560\ \Omega}{10\ \Omega} = 56$$
$V_c = V_{out} = A_v V_{in} = 56(50\text{ mV}) = \mathbf{2.8\ V}$

27. $$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{2.5\text{ V} - 0.7\text{ V}}{100\text{ k}\Omega} = 18\ \mu A$$
$I_C = \beta_{DC} I_B = 250(18\ \mu A) = 4.5\text{ mA}$
$$R_C = \frac{V_{CC} - V_{CE}}{I_C} = \frac{9\text{ V} - 4\text{ V}}{4.5\text{ mA}} = \mathbf{1.1\ k\Omega}$$

28. (a) DC current gain = β_{DC} = **50**
(b) DC current gain = β_{DC} = **125**

Section 4-5 The BJT as a Switch

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

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

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

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

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

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

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

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

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

Section 4-6 The Phototransistor

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

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

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

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

34. $\dfrac{I_{OUT}}{I_{IN}} = 0.6$

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

Section 4-7 Transistor Categories and Packaging

35. See Figure 4-1.

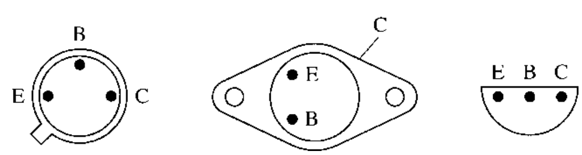


Figure 4-1

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

Section 4-8 Troubleshooting

37. 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.

38. (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).

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

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

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

Application Activity Problems

40. 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

$$I_{R2} = \frac{12\text{ V} - 0.7\text{ V}}{75\text{ k}\Omega} = 151\ \mu\text{A}$$

$$P_{R2} = (151\ \mu\text{A})^2(75\text{ k}\Omega) = \mathbf{1.7\ mW}$$

$$P_{R1} = \frac{(0.7\text{ V})^2}{1.0\text{ M}\Omega} = \mathbf{0.49\ \mu W}$$

$$I_{R4} \cong \frac{12\text{ V} - 0.1\text{ V}}{1.2\text{ k}\Omega} = 9.9\text{ mA}$$

$$P_{R4} = (9.9\text{ mA})^2(1.2\text{ k}\Omega) = 118\text{ mW}$$

$I_{R3} \cong 0$, $P_{R3} = \mathbf{0\ mW}$

$I_{R5} = 0$, $P_{R5} = \mathbf{0\ mW}$

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

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

42. See Figure 4-2.

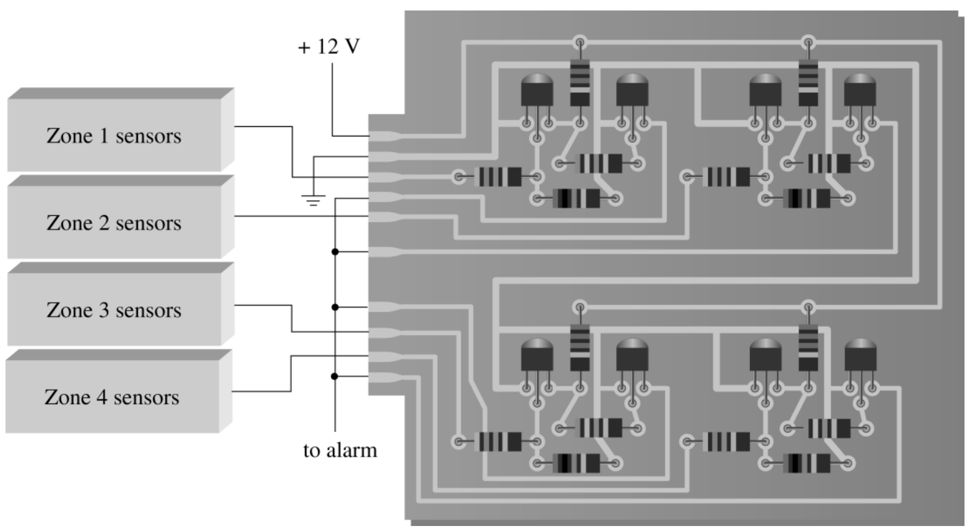


Figure 4-2

Datasheet Problems

43. 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 @ $T_C = 50$°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, $h_{FE(min)} = \mathbf{70}$

44. For an MMBT3904 with $T_A = 65°C$:

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

$= 350\text{ mW} - 40°C(2.8\text{ mW/°C}) = 350\text{ mW} - 112\text{ mW} = \mathbf{238\text{ mW}}$

45. For a PZT3904 with $T_C = 45°C$:

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

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

46. For the circuits of textbook Figure 4-66:

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

No parameter is exceeded.

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

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

(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.

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

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

49. For the circuits of textbook Figure 4-69:

(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

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

$\beta_{DC} - \beta_{DC}\alpha_{DC} = \alpha_{DC}$

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

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

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

$V_{CE} = 15\text{ V} - (180\ \Omega)(75\text{ mA}) = \mathbf{1.5\ V}$

Since $V_{CE(sat)} = 0.3\text{ V}$ @ $I_C = 50\text{ mA}$, the transistor comes out of saturation.

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

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

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

Use the standard value of 240 Ω for R_B.

To avoid saturation, the load resistance cannot exceed about

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

See Figure 4-3.

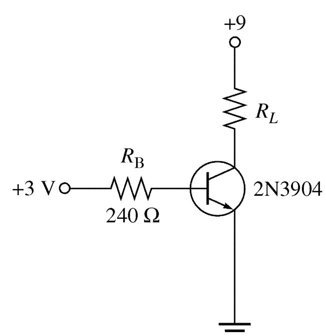


Figure 4-3

53. 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.

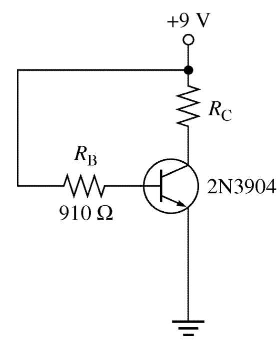


Figure 4-4

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

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

Assuming h_{FE} = 100,

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

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

See Figure 4-5.

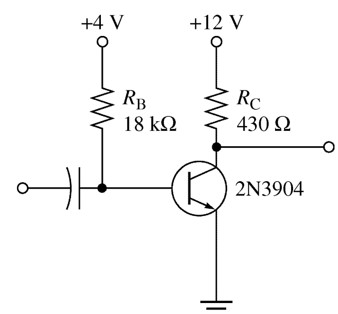


Figure 4-5

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 55 through 62 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).

55. R_B shorted

56. R_C open

57. Collector-emitter shorted

58. Collector-emitter open

59. R_E leaky

60. Collector-emitter shorted

61. R_B open

62. R_C open

Chapter 5
Transistor Bias Circuits

Section 5-1 The DC Operating Point

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

2. $I_C = \beta_{DC}I_B = 75(150\ \mu A) = 11.3$ 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: $V_{CEQ} = \mathbf{6.75\ V}$, $I_{CQ} = \mathbf{11.3\ mA}$

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

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

5. Horizontal intercept (cutoff):
$V_{CE} = V_{CC} = \mathbf{20\ V}$
Vertical intercept (saturation):
$I_{C(sat)} = \dfrac{V_{CC}}{R_C} = \dfrac{20\text{ V}}{10\text{ k}\Omega}\ \mathbf{2\ mA}$

6. $I_B = \dfrac{V_{BB} - 0.7\text{ V}}{R_B}$
$V_{BB} = I_B R_B + 0.7\text{ V} = (20\ \mu A)(1.0\text{ M}\Omega) + 0.7\text{ V} = \mathbf{20.7\ V}$
$I_C = \beta_{DC}I_B = 50(20\ \mu A) = \mathbf{1\ mA}$
$V_{CE} = V_{CC} - I_C R_C = 20\text{ V} - (1\text{ mA})(10\text{ k}\Omega) = \mathbf{10\ V}$

7. See Figure 5-1.
$V_{CE} = V_{CC} - I_C R_C$
$R_C = \dfrac{V_{CC} - V_{CE}}{I_C} = \dfrac{10\text{ V} - 4\text{ V}}{5\text{ mA}} = \mathbf{1.2\ k\Omega}$
$I_B = \dfrac{I_C}{\beta_{DC}} = \dfrac{5\text{ mA}}{100} = 0.05$ mA
$R_B = \dfrac{10\text{ V} - 0.7\text{ V}}{0.05\text{ mA}} = \mathbf{186\ k\Omega}$
$P_{D(min)} = V_{CE}I_C = (4\text{ V})(5\text{ mA}) = \mathbf{20\ mW}$

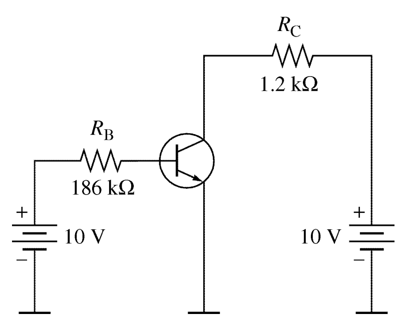


Figure 5-1

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

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

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

The transistor is biased in the linear region because $0 < I_C < I_{C(sat)}$.

9. (a) $I_{C(sat)}$ = **50 mA**

(b) $V_{CE(cutoff)}$ = **10 V**

(c) I_B = **250 μA**

I_C = **25 mA**

V_{CE} = **5 V**

10. (a) $I_C \cong$ **42 mA**

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

$I_B \cong$ **450 μA**

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

See Figure 5-2.

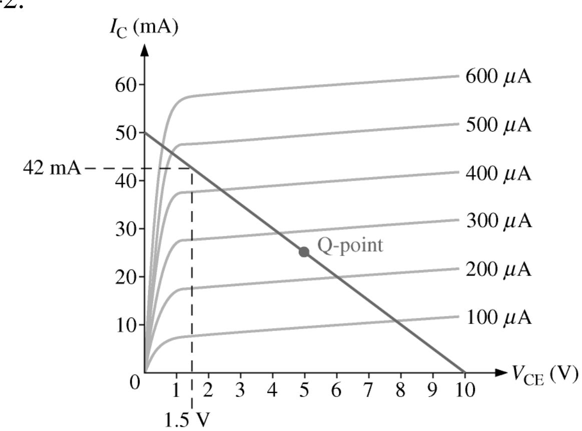


Figure 5-2

Section 5-2 Voltage-Divider Bias

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

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

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

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

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

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

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

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

$$\left(\frac{R_2 \| R_{IN(BASE)}}{R_1 + R_2 \| R_{IN(BASE)}}\right)V_{CC} = V_B$$

$$R_{IN(BASE)} = \frac{\beta_{DC}V_B}{I_E} = \frac{(150)(5.38\text{ V})}{6.88\text{ mA}} = 117\text{ k}\Omega$$

$$(R_2 \| R_{IN(BASE)})V_{CC} = V_B(R_1 + R_2 \| R_{IN(BASE)})$$

$$(R_2 \| R_{IN(BASE)})V_{CC} - (R_2 \| R_{IN(BASE)})V_B = R_1V_B$$

$$(R_2 \| R_{IN(BASE)})(V_{CC} - V_B) = R_1V_B$$

$$(R_2 \| R_{IN(BASE)}) = \frac{R_1V_B}{V_{CC} - V_B} = 12.3\text{ k}\Omega$$

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

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

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

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

$V_E = 1.25\text{ V} - 0.7\text{ V} = 0.55\text{ V}$

$I_E = \dfrac{V_E}{R_E} = \dfrac{0.55\text{ V}}{680\ \Omega} = 809\ \mu\text{A}$

$I_C \cong \mathbf{809\ \mu A}$

$V_{CE} = V_{CC} - I_CR_C - V_E = 15\text{ V} - (809\ \mu\text{A})(1.5\text{ k}\Omega + 680\ \Omega) = \mathbf{13.2\text{ V}}$

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

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

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

$I_C \cong I_E = 1.34\text{ mA}$

$V_C = V_{CC} - I_CR_C = 9\text{ V} - (1.34\text{ mA})(2.2\text{ k}\Omega) = \mathbf{6.05\text{ V}}$

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

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

15. See Figure 5-3.

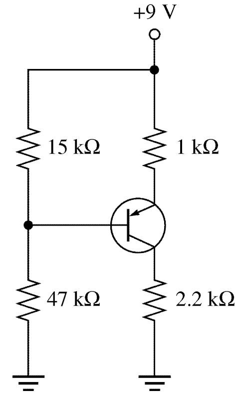


Figure 5-3

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Chapter 5

Section 5-3 Other Bias Methods

19. Using Equation 5-9:

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

$I_C \cong I_E = 1.86$ mA

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

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

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

$V_C = V_{CC} - I_CR_C = 5\text{ V} - (1.86\text{ mA})(1.0\text{ k}\Omega) = \mathbf{3.14\ V}$

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

$V_E = -0.886$ V

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

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

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

21. At 100°C:

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

$I_E = 1.86$ mA (from problem 19)

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

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

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.

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

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

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

24. $V_B = \mathbf{0.7\ V}$

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

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

25. I_C = 1.06 mA from Problem 24.
I_C = 1.06 mA − (0.25)(1.06 mA) = 0.795 mA

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

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

26. I_C = 0.795 mA from Problem 25.
$V_{CE} = V_{CC} - I_C R_C$ = 3 V − (0.795 mA)(2.53 kΩ) = 0.989 V
$P_{D(min)} = V_{CE} I_C$ = (0.989 V)(0.795 mA) = **786 μW**

27. 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 V − (7.87 mA)(1.2 kΩ) = **2.56 V**

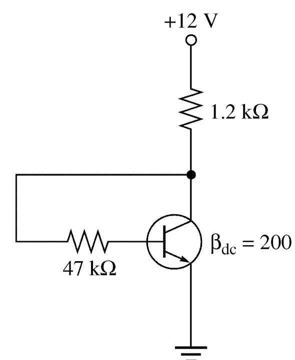


Figure 5-4

28. $V_{BB} = V_{CC}$; V_E = 0 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 μA) = **46.3 mA**
$V_{CE} = V_{CC} - I_C R_C$ = 12 V − (46.3 mA)(100 Ω) = **7.37 V**

29. I_{CQ} = 180(514 μA) = **92.5 mA**
V_{CEQ} = 12 V − (92.5 mA)(100 Ω) = **2.75 V**

30. 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.

31.

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

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

For β_{DC} = 50:
$I_C = \beta_{DC} I_B$ = 50(553 μA) = **27.7 mA**
$V_{CE} = V_{CC} - I_C R_C$ = 9 V − (27.7 mA)(100 Ω) = **6.23 V**
For β_{DC} = 125:
$I_C = \beta_{DC} I_B$ = 125(553 μA) = **69.2 mA**
$V_{CE} = V_{CC} - I_C R_C$ = 9 V − (69.2 mA)(100 Ω) = **2.08 V**
Since $I_C < I_{C(sat)}$ for the range of β_{DC}, the circuit remains **biased in the linear region**.

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

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.

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

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

Section 5-4 Troubleshooting

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

34. $V_1 = \mathbf{0.7\text{ V}}$, $V_2 = \mathbf{0\text{ V}}$

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

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

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

If the problem is corrected,

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

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

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

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

35. (a) Open collector
(b) No problems
(c) Transistor shorted from collector-to-emitter
(d) Open emitter

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

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

For $\beta_{DC} = 100$:

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

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

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

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

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

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

37. (a) The 680 Ω resistor is open:

Meter 1: **10 V**

Meter 2: **floating**

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

Meter 4: **10 V**

(b) The 5.6 kΩ resistor is open.

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

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

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

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: ≅ **0 V**

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

Meter 1: **10 V**

Meter 2: **0 V**

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

Meter 4: **10 V**

Application Activity Problems

38. With R_1 open:

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

39. 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**.

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

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

$V_E = V_B - 0.7\ \text{V} = 2.58\ \text{V}$

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

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

At 48°C: $R_{Therm} = 1.78\ \text{k}\Omega$

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

$V_E = 2.47\ \text{V} - 0.7\ \text{V} = 1.77\ \text{V}$

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

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

At 53°C: $R_{Therm} = 1.28\ \text{k}\Omega$

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

$V_E = 1.93\ \text{V} - 0.7\ \text{V} = 1.23\ \text{V}$

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

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

41. The following measurements would indicate an open CB junction:
$V_C = V_{CC} =$ **+9.1 V**
V_B **normal**
$V_E \cong$ **0 V**

Datasheet Problems

42. For $T = 45°C$ and $R_2 = 2.7\ k\Omega$

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

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

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

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

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

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

$$V_{B(max)} = \left(\frac{2.65\ k\Omega}{2.65\ k\Omega + 5.6\ k\Omega}\right)9.1\ V = \left(\frac{2.65\ k\Omega}{8.25\ k\Omega}\right)9.1\ V = \mathbf{2.92\ V}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

43. At $T = 45°C$ for minimum β_{DC}:
$P_{D(max)} = (5.01\text{ V} - 1.92\text{ V})(4.09\text{ mA}) = (3.09\text{ V})(4.09\text{ mA}) = 12.6\text{ mW}$
At $T = 55°C$ for minimum β_{DC}:
$P_{D(max)} = (7.32\text{ V} - 0.839\text{ V})(1.78\text{ mA}) = (6.48\text{ V})(1.78\text{ mA}) = 11.5\text{ mW}$
For maximum beta values, the results are comparable and nowhere near the maximum.
$P_{D(max)} = 625\text{ mW} - (5.0\text{ m/°C})(30°C) = 475\text{ mW}$
No ratings are exceeded.

44. For the datasheet of Figure 5-49 in the textbook:
(a) For a 2N2222A, $I_{C(max)}$ = **1 A** continuous
(b) For a 2N2118A, $V_{EB(max)}$ = **6.0 V**

45. For a 2N2222A @ $T = 100°C$:
$P_{D(max)} = 0.8\text{ W} - (4.57\text{ mW/°C})(100°C - 25°C) = 0.8\text{ W} - 343\text{ mW} = \mathbf{457\text{ mW}}$

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

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

Advanced Problems

47. See Figure 5-5.

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

Assume $\beta_{DC} = 100$.

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

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

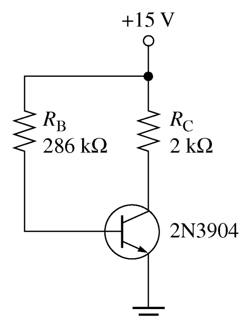


Figure 5-5

48. See Figure 6-6.
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 $I_{CQ} \cong 9.38\text{ mA}$, $V_{CEQ} \cong 5.05\text{ V}$.

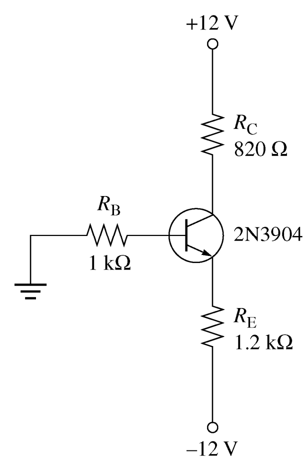


Figure 5-6

49. See Figure 5-7.

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

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

$V_B = 1.5\ V + 0.7\ V = 2.2\ V$

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

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

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

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

$R_1 = 3.09R_2$

$R_1 + R_2 = R_2 + 3.09R_2 = 2.57\ k\Omega$

$4.09R_2 = 2.57\ k\Omega$

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

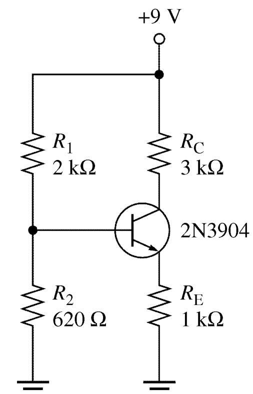


Figure 5-7

So, $R_2 \cong 620\ \Omega$ and $R_1 = 1.92\ k\Omega \cong 2\ k\Omega$.

From this,

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

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

$V_E = 2.13\ V - 0.7\ V = 1.43\ V$

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

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

50. See Figure 5-8.

$\beta_{DC} \cong 75$.

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

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

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

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

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

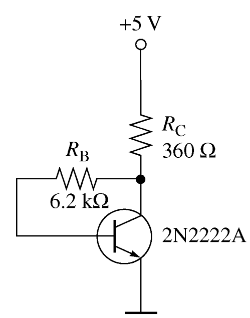


Figure 5-8

51. 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.

52. 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**

53. 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.

54. 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

The solutions showing instrument connections for Problems 55 through 60 are available from the Instructor's Resource Center. See Chapter 2 for instructions. The faults in the circuit files may be accessed using the password *book* (all lowercase).

55. R_C open

56. R_B open

57. R_2 open

58. Collector-emitter shorted

59. R_C shorted

60. 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**.

Section 6-2 Transistor AC Models

3. $r'_e = \dfrac{25\text{ mV}}{I_E} = \dfrac{25\text{ mV}}{3\text{ mA}} = \mathbf{8.33\ \Omega}$

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

5. $I_C = \beta_{DC} I_B = 130(10\ \mu\text{A}) = 1.3\text{ mA}$

$I_E = \dfrac{I_C}{\alpha_{DC}} = \dfrac{1.3\text{ mA}}{0.99} = 1.31\text{ mA}$

$r'_e = \dfrac{25\text{ mV}}{I_E} = \dfrac{25\text{ mV}}{1.31\text{ mA}} = \mathbf{19\ \Omega}$

6. $\beta_{DC} = \dfrac{I_C}{I_B} = \dfrac{2\text{ mA}}{15\ \mu\text{A}} = \mathbf{133}$

$\beta_{ac} = \dfrac{\Delta I_C}{\Delta I_B} = \dfrac{0.35\text{ mA}}{3\ \mu\text{A}} = \mathbf{117}$

Section 6-3 The Common-Emitter Amplifier

7. See Figure 6-1.

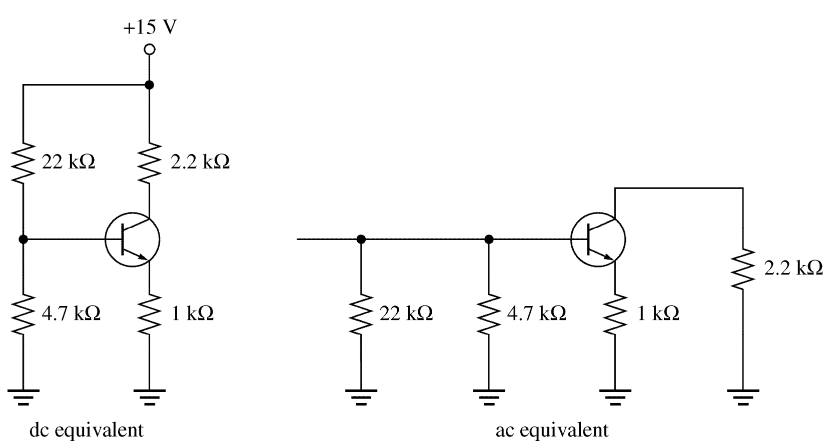


Figure 6-1

Chapter 6

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

14. From Problem 13, $I_E = 2.63$ mA

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

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

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

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

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

Attenuation of the input network is

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

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

$\theta = \mathbf{180°}$

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

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

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

$$r'_e = \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{8.78\text{ mA}} = 2.85\ \Omega$$

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

$$A_{v(\max)} = \frac{R_C}{r'_e} = \frac{330\ \Omega}{2.85\ \Omega} = \mathbf{116}$$

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

$$A_{v(\min)} = \frac{R_C}{R_E + r'_e} = \frac{330\ \Omega}{2.85\ \Omega} = \mathbf{3.21}$$

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

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

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

$$r'_e = \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{8.78\text{ mA}} = 2.85\ \Omega$$

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

$$A_{v(\max)} = \frac{R_C \| R_L}{r'_e} = \frac{330\ \Omega \| 600\ \Omega}{2.85\ \Omega} = \mathbf{74.7}$$

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

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

18. $R_{in} = R_1 \| R_2 \| \beta_{ac} r'_e = 3.3\text{ k}\Omega \| 12\text{ k}\Omega \| 150(3.25\ \Omega) = 410\ \Omega$

Attenuation of the input network is

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

$$A_v = \frac{R_c}{r'_e} = \frac{330\ \Omega \| 1.0\text{ k}\Omega}{3.25\ \Omega} = 76.3$$

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

19. 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 $R_e = 100\ \Omega$.

The gain is reduced to

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

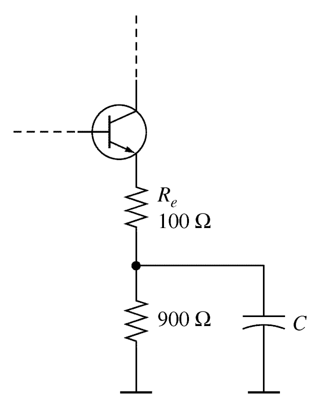


Figure 6-2

Section 6-4 The Common-Collector Amplifier

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

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

$r_e' \cong \dfrac{25\ \text{mV}}{1.06\ \text{mA}} = 23.6\ \Omega$

$A_v = \dfrac{R_E}{R_E + r_e'} = \dfrac{1.0\ \text{k}\Omega}{1.0\ \text{k}\Omega + 23.6\ \Omega} = \mathbf{0.977}$

21. $R_{in} = R_1 \parallel R_2 \parallel \beta_{ac}(r_e' + R_E) \cong R_1 \parallel R_2 \parallel \beta_{ac}R_E = 10\ \text{k}\Omega \parallel 4.7\ \text{k}\Omega \parallel 100\ \text{k}\Omega = \mathbf{3.1\ k\Omega}$

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

22. The voltage gain is **reduced** because $A_v = \dfrac{R_e}{R_e + r_e'}$.

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

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

$r_e' \cong \dfrac{25\ \text{mV}}{I_E} = \dfrac{25\ \text{mV}}{1.06\ \text{mA}} = 23.6\ \Omega$

$A_v = \dfrac{R_E \parallel R_L}{r_e' + R_E \parallel R_L}$

$A_v(r_e' + R_E \parallel R_L) = R_E \parallel R_L$

$R_E \parallel R_L - A_v(R_E \parallel R_L) = A_v r_e'$

$(R_E \parallel R_L)(1 - A_v) = A_v r_e'$

$(R_E \parallel R_L) = \dfrac{A_v r_e'}{(1 - A_v)} = \dfrac{0.9(23.6\ \Omega)}{1 - 0.9} = 212.4\ \Omega$

$R_L R_E = 212.4R_L + 212.4R_E$

$R_L R_E - 212.4R_L = 212.4R_E$

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

24. (a) V_{C1} = **10 V**

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

$V_{E1} = V_{B1} - 0.7\text{ V} = 4\text{ V} - 0.7\text{ V} =$ **3.3 V**
V_{C2} = **10 V**
$V_{B2} = V_{E1}$ = **3.3 V**
$V_{E2} = V_{B2} - 0.7\text{ V} = 3.3\text{ V} - 0.7\text{ V} =$ **2.6 V**

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

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

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

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

$$r'_{e2} \cong \frac{25\text{ mV}}{I_{E2}} = \frac{25\text{ mV}}{1.73\text{ mV}} = \mathbf{14.5\ \Omega}$$

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

$R_{in(base1)} = \beta_{ac1}\beta_{ac2}R_E = (150)(100)(1.5\text{ k}\Omega) = 22.5\text{ M}\Omega$
$R_{in} = 33\text{ k}\Omega \parallel 22\text{ k}\Omega \parallel 22.5\text{ M}\Omega =$ **13.2 kΩ**

25. $R_{in(base)} = \beta_{ac1}\beta_{ac2}R_E = (150)(100)(1.5\text{ k}\Omega) = 22.5\text{ M}\Omega$
$R_{in} = R_2 \parallel R_1 \parallel R_{in(base)} = 22\text{ k}\Omega \parallel 33\text{ k}\Omega \parallel 22.5\text{ M}\Omega = 13.2\text{ k}\Omega$

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

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

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

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

Section 6-5 The Common-Base Amplifier

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

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

$I_E = \dfrac{6.8\text{ V}}{620\ \Omega} = 10.97\text{ mA}$

$R_{in(emitter)} = r'_e \cong \dfrac{25\text{ mV}}{I_E} = \dfrac{25\text{ mA}}{10.97\text{ mA}} = \mathbf{2.28\ \Omega}$

$A_v = \dfrac{R_C}{r'_e} = \dfrac{1.2\text{ k}\Omega}{2.28\ \Omega} = \mathbf{526}$

$A_i \cong \mathbf{1}$

$A_p = A_iA_v \cong \mathbf{526}$

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

Section 6-6 Multistage Amplifiers

29. $A'_v = A_{v1}A_{v2} = (20)(20) = \mathbf{400}$

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

$20 \log A'_v = 30\text{ dB}$

$\log A'_v = \dfrac{30}{20} = 1.5$

$A'_v = \mathbf{31.6}$

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

$I_E = \dfrac{V_E}{R_E} = \dfrac{2.29\text{ V}}{1.0\text{ k}\Omega} = 2.29\text{ mA}$

$r'_e \cong \dfrac{25\text{ mV}}{I_E} = \dfrac{25\text{ mV}}{2.29\text{ mA}} = 10.9\ \Omega$

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

$A_{v1} = \dfrac{R_C \parallel R_{in(2)}}{r'_e} = \dfrac{3.3\text{ k}\Omega \parallel 1.48\text{ k}\Omega}{10.9\ \Omega} = \mathbf{93.6}$

$A_{v2} = \dfrac{R_C}{r'_e} = \dfrac{3.3\text{ k}\Omega}{10.9\ \Omega} = \mathbf{303}$

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

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

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

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

32. (a) $A_{v1} = \dfrac{R_C \parallel R_{in(2)}}{r'_e} = \dfrac{3.3\text{ k}\Omega \parallel 1.48\text{ k}\Omega}{10.9\ \Omega}$ = **93.6**

$A_{v2} = \dfrac{R_C \parallel R_L}{r'_e} = \dfrac{3.3\text{ k}\Omega \parallel 18\text{ k}\Omega}{10.9\ \Omega}$ = **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

$\dfrac{R_{in(1)}}{R_{in(1)} + R_s} = \dfrac{1.48\text{ k}\Omega}{1.48\text{ k}\Omega + 75\ \Omega} = 0.95$

$A'_v = (0.95)A_{v1}A_{v2} = (0.95)(93.6)(256) =$ **22,764**

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

$A_{v2(\text{dB})} = 20\log(256) =$ **48.2 dB**

$A'_{v(\text{dB})} = 20\log(22{,}764) =$ **87.1 dB**

33. $V_{B1} = \left(\dfrac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\dfrac{22\text{ k}\Omega}{122\text{ k}\Omega}\right)12\text{ V}$ = **2.16 V**

$V_{E1} = V_{B1} - 0.7\text{ V} =$ **1.46 V**

$I_{C1} \cong I_{E1} = \dfrac{V_{E1}}{R_4} = \dfrac{1.46\text{ V}}{4.7\text{ k}\Omega} = 0.311\text{ mA}$

$V_{C1} = V_{CC} - I_{C1}R_3 = 12\text{ V} - (0.311\text{ mA})(22\text{ k}\Omega) =$ **5.16 V**

$V_{B2} = V_{C1} =$ **5.16 V**

$V_{E2} = V_{B2} - 0.7\text{ V} = 5.16\text{ V} - 0.7\text{ V} =$ **4.46 V**

$I_{C2} \cong I_{E2} = \dfrac{V_{E2}}{R_6} = \dfrac{4.46\text{ V}}{10\text{ k}\Omega} = 0.446\text{ mA}$

$V_{C2} = V_{CC} - I_{C2}R_5 = 12\text{ V} - (0.446\text{ mA})(10\text{ k}\Omega) =$ **7.54 V**

$r'_{e2} \cong \dfrac{25\text{ mV}}{I_{E2}} = \dfrac{25\text{ mV}}{0.446\text{ mA}} = 56\ \Omega$

$R_{in(2)} = \beta_{ac} r'_{e2} = (125)(56\ \Omega) = 7\text{ k}\Omega$

$r'_{e1} \cong \dfrac{25\text{ mV}}{I_{E1}} = \dfrac{25\text{ mV}}{0.311\text{ mA}} = 80.4\ \Omega$

$A_{v1} = \dfrac{R_3 \parallel R_{in(2)}}{r'_{e1}} = \dfrac{22\text{ k}\Omega \parallel 7\text{ k}\Omega}{80.4\ \Omega}$ = **66**

$A_{v2} = \dfrac{R_5}{r'_{e2}} = \dfrac{10\text{ k}\Omega}{56\ \Omega}$ = **179**

$A'_v = A_{v1}A_{v2} = (66)(179) =$ **11,814**

34. (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**

35. (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) $20 \log\left(\frac{V_2}{V_1}\right) = 40 \text{ dB}$

$\log\left(\frac{V_2}{V_1}\right) = \frac{40}{20} = 2$

$\frac{V_2}{V_1} = \mathbf{100}$

Section 6-7 The Differential Amplifier

36. 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:

$$V_{OUT} = V_{C(Q2)} - V_{C(Q1)} = 4.54 \text{ V} - 4.49 \text{ V} = 0.05 \text{ V} = \mathbf{50\ mV}$$

37. V_1 measures the differential output voltage.
V_2 measures the non-inverting input voltage.
V_3 measures the single-ended output voltage.
V_4 measures the differential input voltage.
I_1 measures the bias current.

38. 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:

$$V_{OUT} = V_{C(Q2)} - V_{C(Q1)} = (V_{CC} - V_{R_{C2}}) - (V_{CC} - V_{R_{C1}}) = V_{R_{C1}} - V_{R_{C2}}$$

$$= 6.89\text{ V} - 6.58\text{ V} = 0.31\text{ V} = \mathbf{310\text{ mV}}$$

39. (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

40. $V_E = \left(\dfrac{R_1}{R_1 + R_2}\right)10\text{ V} - 0.7\text{ V} = \left(\dfrac{10\text{ k}\Omega}{57\text{ k}\Omega}\right)10\text{ V} - 0.7\text{ V} = 1.05\text{ V}$

$I_E = \dfrac{V_E}{R_4} = \dfrac{1.05\text{ V}}{1.0\text{ k}\Omega} = 1.05\text{ mA}$

$V_C = 10\text{ V} - (1.05\text{ mA})(4.7\text{ k}\Omega) = 5.07\text{ V}$

$V_{CE} = 5.07\text{ V} - 1.05\text{ V} = 4.02\text{ V}$

$r'_{CE} \cong \dfrac{V_{CE}}{I_E} = \dfrac{4.02\text{ V}}{1.05\text{ mA}} = 3.83\text{ k}\Omega$

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:

$\left(r'_{CE} + R_4\right) \parallel R_{IN(2)} = (3.83\text{ k}\Omega + 1.0\text{ k}\Omega) \parallel 9.26\text{ k}\Omega = 3.17\text{ k}\Omega$

$V_{C1} = \left(\dfrac{3.17\text{ k}\Omega}{3.17\text{ k}\Omega + 4.7\text{ k}\Omega}\right)10\text{ V} = \mathbf{4.03\text{ V}}$

41. Q_1 is in **cutoff**. $I_C = 0$ A, so $V_{C2} =$ **10 V**.

42. (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.

43. $r'_e = 10.9\ \Omega$ $R_{in} = 1.48\ \text{k}\Omega$
$A_{v1} = 93.6$ $A_{v2} = 302$

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

Application Activity Problems

44. For the block diagram of textbook Figure 6-46 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.

45. (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)

46. $R_7 = 220\ \Omega$ will bias Q_2 off.

47. (a) Q_1 is in **cutoff**.
(b) $V_{C1} = V_{\text{EE}}$
(c) V_{C2} is unchanged and at **5.87 V**.

Datasheet Problems

48. From the datasheet in textbook Figure 6-63:
(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.

49. From the 2N3947 datasheet in Figure 6-63:
(a) For a 2N3947, $\beta_{ac(\max)} = \mathbf{700}$
(b) For a 2N3947, $r'_{e(\max)} = \dfrac{h_{re}}{h_{oe}} = \dfrac{20\times10^{-4}}{50\ \mu\text{S}} = \mathbf{40\ \Omega}$

(c) For a 2N3947, $r'_{c(\max)} = \dfrac{h_{re}+1}{h_{oe}} = \dfrac{20\times10^{-4}+1}{50\ \mu\text{S}}$ = **20 kΩ**

50. For maximum current gain, a **2N3947** should be used.

Advanced Problems

51. In the circuit of textbook Figure 6-62, a leaky coupling capacitor would affect the biasing of the transistors, attenuate the ac signal, and decrease the frequency response.

52. See Figure 6-3.

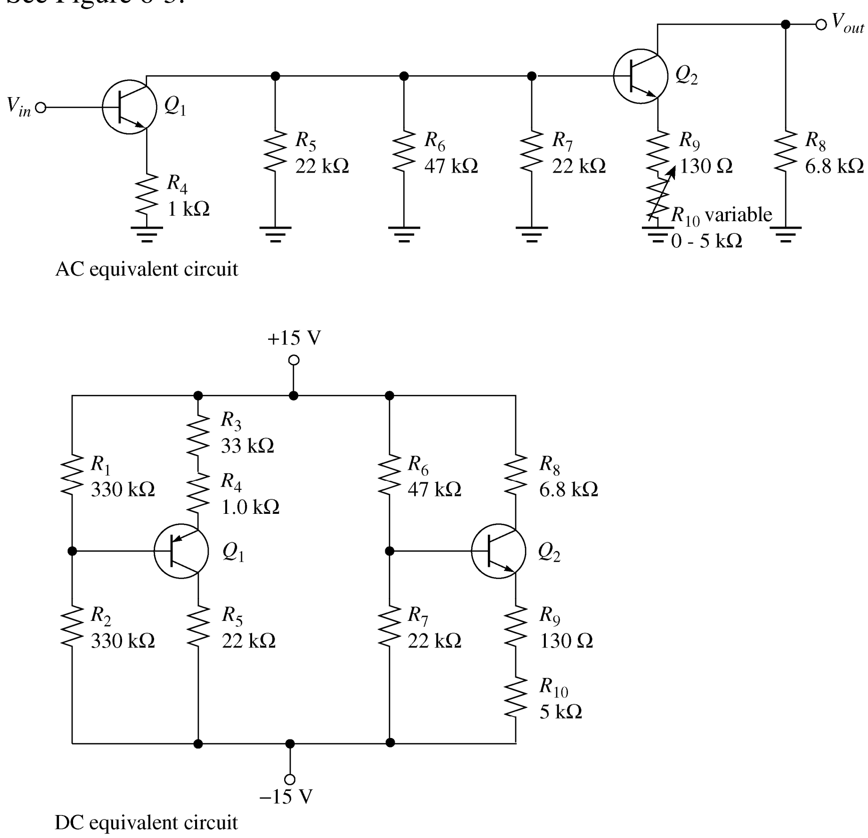


Figure 6-3

53. For the 2nd stage:

$$I_{R6\text{-}7} = \frac{30\text{ V}}{R_6 + R_7} = \frac{30\text{ V}}{69\text{ k}\Omega} = 435\ \mu\text{A}$$

$V_{B2} = V_{CC} - I_{R6\text{-}7}R_6 = 15\text{ V} - (435\mu\text{A})(47\text{ k}\Omega)$
$= 15\text{ V} - 20.5\text{ V} = -5.5\text{ V}$

$$I_{E2} = \frac{V_{E2}}{R_9 + R_{10}} = \frac{-5.5\text{ V} - 0.7\text{ V}}{5.13\text{ k}\Omega} = -1.21\text{ mA}$$

$$r'_{e2} = \frac{25\text{ mV}}{1.21\text{ mA}} = 20.7\ \Omega$$

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:

$$A_{v(2)} = \frac{R_8 \| R_L}{R_9 + r'_{e2}} = \frac{6.8\text{ k}\Omega \| 10\text{ k}\Omega}{150.7\ \Omega} = \frac{4.05\text{ k}\Omega}{150.7\ \Omega} = 26.9$$

To keep unloaded gain:

$$\frac{4.05\text{ k}\Omega}{R_9 + 20.7\ \Omega} = 45.1$$

$4.05\text{ k}\Omega = 45.1(R_9 + 20.7\ \Omega) = 45.1R_9 + 934\ \Omega$

$$R_9 = \frac{4.05\text{ k}\Omega - 934\ \Omega}{45.1} = \mathbf{69.1\ \Omega}$$

54. $R_C > (100)(330\ \Omega) = 33\text{ k}\Omega$
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.
$R_C = 100(R_E + r'_e)$

$$r'_e = \frac{25\text{ mV}}{I_E}$$

$12\text{ V} - I_CR_C = 8.46\text{ V}$
$I_CR_C = 3.54\text{ V}$
$I_C(100(R_E + r'_e)) = 3.54\text{ V}$

$$I_C\left(100\left(330\ \Omega + \frac{25\text{ mV}}{I_C}\right)\right) \cong 3.54\text{ V}$$

$(33\text{ k}\Omega)I_C + 2.5\text{ V} = 3.54\text{ V}$
$I_C = 31.4\ \mu\text{A}$

$$r'_e \cong \frac{25\text{ mV}}{31.4\ \mu\text{A}} = 797\ \Omega$$

$R_C = 100(330\ \Omega + 797\ \Omega) = 113\text{ k}\Omega$
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 kΩ) = 77 kΩ. Let R_E = 68 kΩ.

$V_E = (31.4\ \mu\text{A})(68\text{ k}\Omega) = 2.14\text{ V}$

$V_B = 2.14\text{ V} + 0.7\text{ V} = 2.84\text{ V}$

$$\frac{R_2}{R_1} = \frac{2.84\text{ V}}{9.16\text{ V}} = 0.310$$

$R_2 = 0.310R_1$. If R_1 = 20 kΩ, R_2 = 6.2 kΩ.

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.

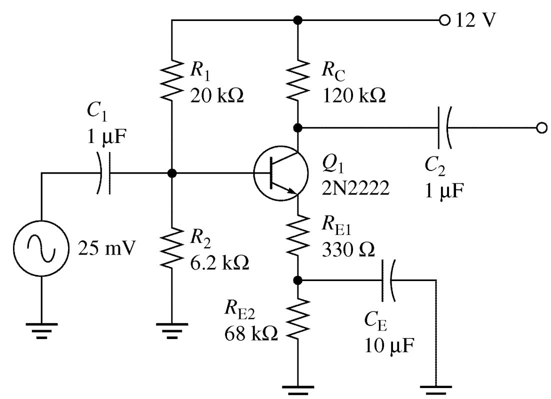


Figure 6-4

55. See Figure 6-5.

$R_{in} = 120\text{ k}\Omega \parallel 120\text{ k}\Omega \parallel (100)(5.1\text{ k}\Omega) = 53.6\text{ k}\Omega$ minimum

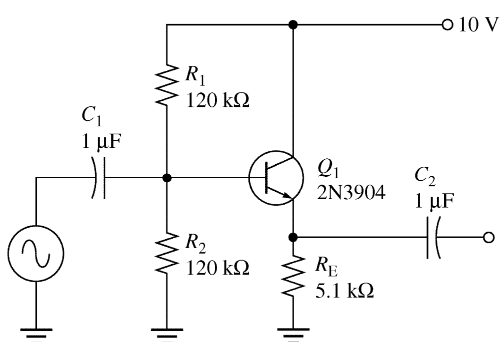


Figure 6-5

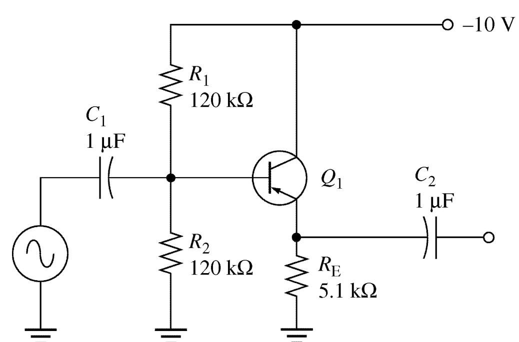


Figure 6-6

56. See Figure 6-6.

57. See Figure 6-7.

$$I_C = \frac{6\text{ V} - 0.7\text{ V}}{510\ \Omega + 2\text{ k}\Omega/100} = 10\text{ mA}$$

$$r'_e = \frac{25\text{ mV}}{10\text{ mA}} = 2.5\ \Omega$$

$$A_v = \frac{180\ \Omega}{2.5\ \Omega} = 72.4$$

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.

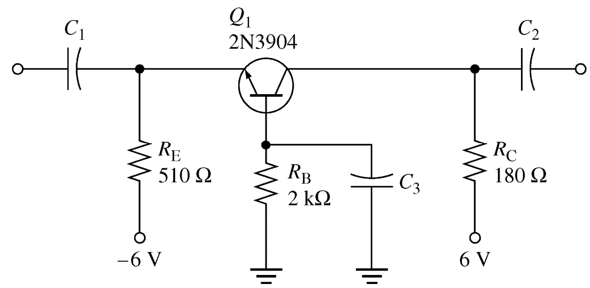


Figure 6-7

58. Assuming $\beta_{ac} = 200$,

$$C_1 = \frac{1}{2\pi f_c R} = \frac{1}{2\pi(100\text{ Hz})(330\text{ k}\Omega \,\|\, 330\text{ k}\Omega \,\|\, (200 \times 34\text{ k}\Omega))}$$

$$= \frac{1}{2\pi(100\text{ Hz})(161\text{ k}\Omega)} = \mathbf{0.01\ \mu F}$$

$$C_2 = \frac{1}{2\pi f_c R} = \frac{1}{2\pi(100\text{ Hz})(22\text{ k}\Omega + 47\text{ k}\Omega \,\|\, 22\text{ k}\Omega \,\|\, (200 \times 5.13\text{ k}\Omega))}$$

$$= \frac{1}{2\pi(100\text{ Hz})(36.98\text{ k}\Omega)} = \mathbf{0.043\ \mu F}$$

59. $I_C \cong I_E$

$$A_v = \frac{R_C}{r'_e} \cong \frac{R_C}{25\text{ mV}/I_E} \cong \frac{R_C}{25\text{ mV}/I_C} = \frac{R_C I_C}{25\text{ mV}} = \frac{V_{R_C}}{25\text{ mV}} = 40V_{R_C}$$

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 60 through 65 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).

60. C_2 open

61. C_2 shorted

62. R_E leaky

63. C_1 open

64. C_2 open

65. C_3 open

Chapter 7
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) $A_v = \dfrac{R_L}{R_{E1} + r_e'} = \dfrac{100\ \Omega}{8.2\ \Omega + 0.37\ \Omega} = \mathbf{11.7}$

$R_{in} = \beta_{ac}(R_{E1} + r_e') \parallel R_1 \parallel R_2$

$= 100\ (8.2\ \Omega + 0.37\ \Omega) \parallel 330\ \Omega \parallel 1.0\ \text{k}\Omega = 192\ \Omega$

$A_p = A_v^2\left(\dfrac{R_{in}}{R_L}\right) = 11.7^2\left(\dfrac{192\ \Omega}{100\ \Omega}\right) = \mathbf{263}$

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.

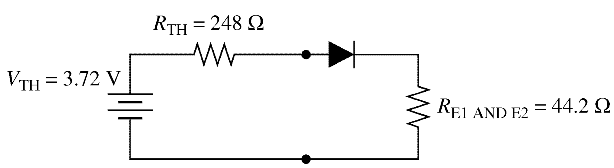


Figure 7-1

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.

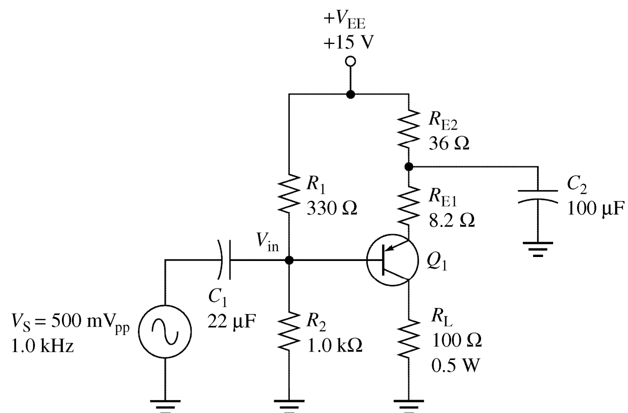


Figure 7-2

4. A CC amplifier has a voltage gain of approximately 1. Therefore, $A_p = \dfrac{R_{in}}{R_{out}} = \dfrac{2.2\text{ k}\Omega}{50\ \Omega} = \mathbf{44}$

5. (a) $V_{TH} = \left(\dfrac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\dfrac{510\ \Omega}{1190\ \Omega}\right)12\text{ V} = 5.14\text{ V}$

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = \frac{(680\ \Omega)(510\ \Omega)}{1190\ \Omega} = 291\ \Omega$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{5.14\text{ V} - 0.7\text{ V}}{79.7\ \Omega + 291\ \Omega / 125} = 54\text{ mA}$$

$I_C \cong I_E = \mathbf{54\ mA}$
$V_C = V_{CC} - I_C R_C = 12\text{ V} - (54\text{ mA})(100\ \Omega) = 6.6\text{ V}$
$V_E = I_E R_E = (54\text{ mA})(79.7\ \Omega) = 4.3\text{ V}$
$V_{CE} = V_C - V_E = 6.6\text{ V} - 4.3\text{ V} = \mathbf{2.3\ V}$

(b) $V_{TH} = \left(\dfrac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\dfrac{4.7\text{ k}\Omega}{16.7\text{ k}\Omega}\right)12\text{ V} = 3.38\text{ V}$

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = \frac{(12\text{ k}\Omega)(4.7\text{ k}\Omega)}{16.7\text{ k}\Omega} = 3.38\text{ k}\Omega$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{3.38\text{ V} - 0.7\text{ V}}{142\ \Omega + 3.38\text{ k}\Omega / 120} = 15.7\text{ mA}$$

$I_C \cong I_E = \mathbf{15.7\ mA}$
$V_C = V_{CC} - I_C R_C = 12\text{ V} - (15.7\text{ mA})(470\ \Omega) = 4.62\text{ V}$
$V_E = I_E R_E = (15.7\text{ mA})(142\ \Omega) = 2.23\text{ V}$
$V_{CE} = V_C - V_E = 4.62\text{ V} - 2.23\text{ V} = \mathbf{2.39\ V}$

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 7-43(a):
From Problem 5(a),
$I_{CQ} = 54$ mA; $V_{CEQ} = 2.3$ V
$R_e = R_C \| R_L = 100\ \Omega \| 100\ \Omega = 50\ \Omega$
$V_{ce(cutoff)} = V_{CEQ} + I_{CQ}R_c = 2.3\text{ V} + (54\text{ mA})(50\ \Omega) = 5\text{ V}$
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),
$I_{CQ} = 15.7$ mA; $V_{CEQ} = 2.39$ V
$R_e = R_C \| R_L = 470\ \Omega \| 470\ \Omega = 235\ \Omega$
$V_{ce(cutoff)} = V_{CEQ} + I_{CQ}R_c = 2.39\text{ V} + (15.7\text{ mA})(235\ \Omega) = 6.08\text{ V}$
Since V_{CEQ} is closer to saturation, I_c is limited to

$$I_{c(p)} = \frac{V_{CEQ}}{R_c} = \frac{2.39\text{ V}}{235\ \Omega} = \mathbf{10.2\ mA}$$

V_{out} is limited to
$V_{out(p)} = V_{CEQ} = \mathbf{2.39\ V}$

8. (a) $A_p = A_v^2\left(\frac{R_{in}}{R_L}\right)$

$$A_v \cong \frac{R_c}{R_{E1}} = \frac{R_C \| R_L}{R_{E1}} = \frac{100\ \Omega \| 100\ \Omega}{4.7\ \Omega} = \frac{50\ \Omega}{4.7\ \Omega} = \mathbf{10.6}$$

$$R_{in} = R_1 \| R_2 \| R_{in(base)} = R_1 \| R_2 \| \beta_{ac}R_{E1}$$

$$R_{in} = 680\ \Omega \| 510\ \Omega \| (125)(4.7\ \Omega) = 680\ \Omega \| 510\ \Omega \| 588\ \Omega = 195\ \Omega$$

$$A_p = (10.6)^2\left(\frac{195\ \Omega}{100\ \Omega}\right) = \mathbf{219}$$

(b)

$$A_v \cong \frac{R_c}{R_{E1}} = \frac{R_C \| R_L}{R_{E1}} = \frac{470\ \Omega \| 470\ \Omega}{22\ \Omega} = \frac{235\ \Omega}{22\ \Omega} = \mathbf{10.7}$$

$$R_{in} = 12\text{ k}\Omega \| 4.7\text{ k}\Omega \| (120)(22\ \Omega) = 12\text{ k}\Omega \| 4.7\text{ k}\Omega \| 2.64\text{ k}\Omega = 1.48\text{ k}\Omega$$

$$A_p = (10.7)^2\left(\frac{1.48\text{ k}\Omega}{470\ \Omega}\right) = \mathbf{361}$$

9. $V_{TH} = \left(\dfrac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\dfrac{1\ \text{k}\Omega}{5.7\ \text{k}\Omega}\right)24\ \text{V} = 4.2\ \text{V}$

$R_{TH} = \dfrac{R_1R_2}{R_1 + R_2} = \dfrac{(4.7\ \text{k}\Omega)(1\ \text{k}\Omega)}{5.7\ \text{k}\Omega} = 825\ \Omega$

$I_E = \dfrac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \dfrac{4.2\ \text{V} - 0.7\ \text{V}}{130\ \Omega + 825\ \Omega / 90} = 25\ \text{mA}$

$I_C \cong I_E = 25\ \text{mA}$

$V_C = V_{CC} - I_CR_C = 24\ \text{V} - (25\ \text{mA})(560\ \Omega) = 10\ \text{V}$

$V_E = I_ER_E = (25\ \text{mA})(130\ \Omega) = 3.25\ \text{V}$

$V_{CEQ} = V_C - V_E = 10\ \text{V} - 3.25\ \text{V} = 6.75\ \text{V}$

$P_{D(min)} = P_{DQ} = I_{CQ}V_{CEQ} = (25\ \text{mA})(6.75\ \text{V}) = \mathbf{169\ mW}$

10. From Problem 9: $I_{CQ} = 25\ \text{mA}$ and $V_{CEQ} = 6.75\ \text{V}$

$V_{ce(cutoff)} = V_{CEQ} + I_{CQ}R_c = 6.75\ \text{V} + (25\ \text{mA})(264\ \Omega) = 13.5\ \text{V}$

$P_{out} = 0.5I_{CQ}^2R_c = 0.5(25\ \text{mA})^2(264\ \Omega) = \mathbf{82.5\ mW}$

$\eta = \dfrac{P_{out}}{P_{DC}} = \dfrac{P_{out}}{V_{CC}I_{CC}} = \dfrac{P_{out}}{V_{CC}I_{CQ}} = \dfrac{82.5\ \text{mW}}{(24\ \text{V})(25\ \text{mA})} = \mathbf{0.138}$

Section 7-2 The Class B and Class AB Push-Pull Amplifiers

11. (a) $V_{B(Q1)} = 0\ \text{V} + 0.7\ \text{V} = \mathbf{0.7\ V}$

$V_{B(Q2)} = 0\ \text{V} - 0.7\ \text{V} = \mathbf{-0.7\ V}$

$V_E = \mathbf{0\ V}$

$I_{CQ} = \dfrac{V_{CC} - (-V_{CC}) - 1.4\ \text{V}}{R_1 + R_2} = \dfrac{9\ \text{V} - (-9\ \text{V}) - 1.4\ \text{V}}{1.0\ \text{k}\Omega + 1.0\ \text{k}\Omega} = \mathbf{8.3\ mA}$

$V_{CEQ(Q1)} = \mathbf{9\ V}$

$V_{CEQ(Q2)} = \mathbf{-9\ V}$

(b) $V_{out} = V_{in} = 5.0\ \text{V rms}$

$P_{out} = \dfrac{(V_{out})^2}{R_L} = \dfrac{5.0\ \text{V}^2}{50\ \Omega} = \mathbf{0.5\ W}$

12. $I_{c(sat)} = \dfrac{V_{CC}}{R_L} = \dfrac{9.0\ \text{V}}{50\ \Omega} = 180\ \text{mA}$

$V_{ce(cutoff)} = 9\ \text{V}$

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 11) and the dc load line rises vertically through this point.

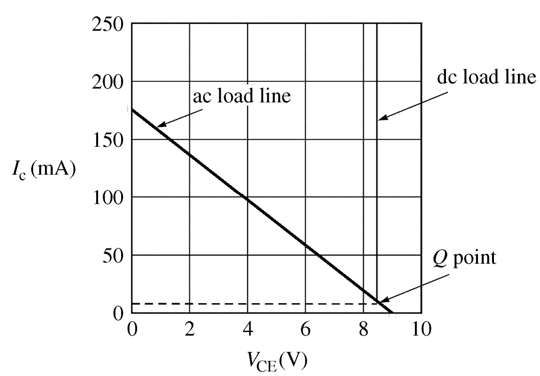


Figure 7-3

13. $R_{in} = \beta_{ac}(r_e' + R_L)R_1 \| R_2$
From Problem 11,
$I_{CQ} = 8.3$ mA
so, $I_E \cong 8.3$ mA

$$r_e' = \frac{25\text{ mV}}{8.3\text{ mA}} = 3\ \Omega$$

$$R_{in} = 100(53\ \Omega)\|1.0\text{ k}\Omega\|1.0\text{ k}\Omega$$
$$= 5300\ \Omega\|1.0\text{ k}\Omega\|1.0\text{ k}\Omega = \mathbf{457\ \Omega}$$

14. The DC voltage at the output becomes negative instead of 0 V.

15. (a) $V_{B(Q1)} = 7.5\text{ V} + 0.7\text{ V} = \mathbf{8.2\ V}$
$V_{B(Q2)} = 7.5\text{ V} - 0.7\text{ V} = \mathbf{6.8\ V}$

$$V_E = \frac{15\text{ V}}{2} = \mathbf{7.5\ V}$$

$$I_{CQ} = \frac{V_{CC} - 1.4\text{ V}}{R_1 + R_2} = \frac{15\text{ V} - 1.4\text{ V}}{1.0\text{ k}\Omega + 1.0\text{ k}\Omega} = \mathbf{6.8\ mA}$$

$V_{CEQ(Q1)}) = 15\text{ V} - 7.5\text{ V} = \mathbf{7.5\ V}$
$V_{CEQ(Q2)} = 0\text{ V} - 7.5\text{ V} = \mathbf{-7.5\ V}$

(b) $V_{in} = V_{out} = 10\text{ V}_{pp} = 3.54$ V rms

$$P_L = \frac{(V_L)^2}{R_L} = \frac{(3.54\text{ V})^2}{75\ \Omega} = \mathbf{167\ mW}$$

16. (a) Maximum peak voltage = 7.5 V_p. 7.5 V_p = 5.30 V rms

$$P_{L(max)} = \frac{(V_L)^2}{R_L} = \frac{(5.30\text{ V})^2}{75\ \Omega} = \mathbf{375\ mW}$$

(b) Maximum peak voltage = 12 V_p. 12 V_p = 8.48 V rms

$$P_{L(max)} = \frac{(V_L)^2}{R_L} = \frac{(8.48\text{ V})^2}{75\ \Omega} = \mathbf{960\ mW}$$

17. (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

18. $R_{in} = \beta_{ac}(r_e' + R_L)R_1 \| R_2$
From Problem 15:
$I_{CQ} = 6.8$ mA
so, $I_E \cong 6.8$ mA

$$r_e' = \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{6.8\text{ mA}} = 3.68\ \Omega$$

$$R_{in} = 200(78.7\ \Omega) \parallel 1\text{ k}\Omega \parallel 1\text{ k}\Omega = 485\ \Omega$$

$$V_b = \left(\frac{485\ \Omega}{485\ \Omega + 50\ \Omega}\right)1\text{ V} = \mathbf{0.91\ V\ rms}$$

Section 7-3 The Class C Amplifier

19. $$P_{D(avg)} = \left(\frac{t_{on}}{T}\right)V_{CE(sat)}I_{C(sat)} = (0.1)(0.18\text{ V})(25\text{ mA}) = \mathbf{450\ \mu W}$$

20. $$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(10\text{ mH})(0.001\ \mu\text{F})}} = \mathbf{50.3\ kHz}$$

21. $$V_{out(pp)} = 2V_{CC} = 2(12\text{ V}) = \mathbf{24\ V}$$

22. $$P_{out} = \frac{0.5V_{CC}^2}{R_c} = \frac{0.5(15\text{ V})^2}{50\ \Omega} = 2.25\text{ W}$$

$$P_{D(avg)} = \left(\frac{t_{on}}{T}\right)V_{CE(sat)}I_{C(sat)} = (0.1)(0.18\text{ V})(25\text{ mA}) = 0.45\text{ mW}$$

$$\eta = \frac{P_{out}}{P_{out} + P_{D(avg)}} = \frac{2.25\text{ W}}{2.25\text{ W} + 0.45\text{ mW}} = \mathbf{0.9998}$$

Section 7-4 Troubleshooting

23. With C_1 open, only the negative half of the input signal appears across R_L.

24. One of the transistors is open between the collector and emitter or a coupling capacitor is open.

25. (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

Application Activity Problems

26. For the block diagram of textbook Figure 7-34 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.

27. For the circuit of Figure 7-35 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.

28. For the circuit of Figure 7-35 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).

29. On the circuit board of Figure 7-49, the vertically oriented diode has been installed backwards.

Datasheet Problems

30. From the BD135 datasheet of textbook Figure 7-50:
(a) $\beta_{DC(min)} = \mathbf{40}$ @ $I_C = 150$ mA, $V_{CE} = 2$ V
$\beta_{DC(min)} = \mathbf{25}$ @ $I_C = 5$ mA, $V_{CE} = 2$ V
(b) For a BD135, $V_{CE(max)} = V_{CEO} =$ **45 V**
(c) $P_{D(max)} =$ **12.5 W** @ $T_C = 25°C$
(d) $I_{C(max)} = 1.5$ A

31. $P_D =$ **10 W** @ 50°C from graph in Figure 7-50.

32. $P_D = 1$ W @ 50°C. Extrapolating from the case temperature graph in Figure 7-50, since $P_D = 1.25$ W @ 25°C ambient. This derating gives 1 W.

33. 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.

34. $h_{FE} \cong 89$ @ $I_C = 20$ mA

Advanced Problems

35. 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.

36. $I_{C(sat)} = \dfrac{24\text{ V}}{330\,\Omega + 100\,\Omega} = \dfrac{24\text{ V}}{430\,\Omega} = \mathbf{55.8\ mA}$

$V_{CE(cutoff)} = \mathbf{24\ V}$

$V_{BQ} = \left(\dfrac{1.0\text{ k}\Omega}{1.0\text{ k}\Omega + 4.7\text{ k}\Omega}\right)24\text{ V} = 4.21\text{ V}$

$V_{EQ} = 4.21\text{ V} - 0.7\text{ V} = 3.51\text{ V}$

$I_{EQ} \cong I_{CQ} = \dfrac{3.51\text{ V}}{100\,\Omega} = 35.1\text{ mA}$

$R_c = 330\,\Omega \parallel 330\,\Omega = 165\,\Omega$

$V_{CQ} = 24\text{ V} - (35.1\text{ mA})(330\,\Omega) = 12.4\text{ V}$

$V_{CEQ} = 12.4\text{ V} - 3.51\text{ V} = 8.90\text{ V}$

$I_{c(sat)} = 35.1\text{ mA} + \dfrac{8.90\text{ V}}{165\,\Omega} = \mathbf{89.1\ mA}$

$V_{ce(cutoff)} = 8.90\text{ V} + (35.1\text{ mA})(165\,\Omega) = \mathbf{14.7\ V}$

See Figure 7-4.

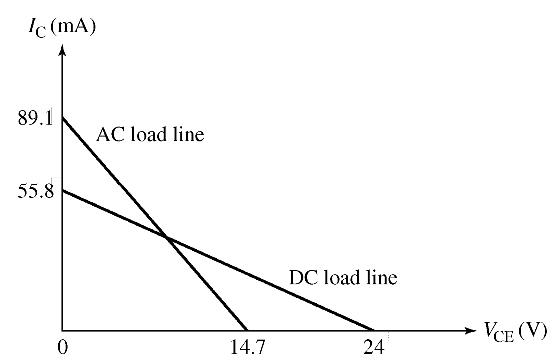


Figure 7-4

37. See Figure 7-5.

$I_{R1} \cong I_{R2} = \dfrac{15\text{ V}}{86\ \Omega} = 174\text{ mA}$

$V_B \cong \left(\dfrac{18\ \Omega}{86\ \Omega}\right)15\text{ V} = 3.14\text{ V}$

$V_E = 3.14\text{ V} - 0.7\text{ V} = 2.44\text{ V}$

$I_E \cong I_C = \dfrac{2.44\text{ V}}{4.85\ \Omega} = 503\text{ mA}$

$V_C = 15\text{ V} - (10\ \Omega)(503\text{ mA}) = 9.97\text{ V}$

$V_{CE} = 7.53\text{ V}$

$r'_e = \dfrac{25\text{ mV}}{503\text{ mA}} = 0.05\ \Omega$

The ac resistance affecting the load line is

$R_c + R_e + r'_e = 10\ \Omega$

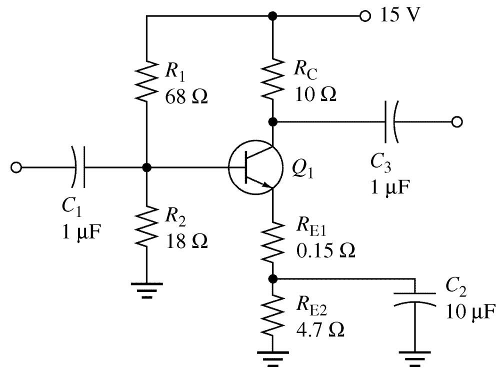


Figure 7-5

$\beta_{ac} = \beta_{DC} \geq 100$

$I_{c(sat)} = 503\text{ mA} + \dfrac{7.53\text{ V}}{10.2\ \Omega} = 1.24\text{ A}$

$V_{ce(cutoff)} = 7.53\text{ V} + (503\text{ mA})(10.2\ \Omega) = 12.7\text{ V}$

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 $P_{out} \geq 1$ W for $R_L \geq 37.7\ \Omega$. (39 Ω standard)

38. Preamp quiescent current:

$I_1 = I_2 = \dfrac{30\text{ V}}{660\text{ k}\Omega} = 45\ \mu\text{A}$

$I_3 = I_4 = I_5 = \dfrac{15\text{ V} - 0.7\text{ V}}{34\text{ k}\Omega} = 421\ \mu\text{A}$

$I_6 = I_7 = \dfrac{30\text{ V}}{69\text{ k}\Omega} = 435\ \mu\text{A}$

$V_{B2} = 15\text{ V} - (435\ \mu\text{A})(47\text{ k}\Omega) = -5.45\text{ V}$

$I_8 = I_9 = I_{10} = \dfrac{-15\text{ V} - (-5.45\text{ V} - 0.7\text{ V})}{5.13\text{ k}\Omega} = 1.73\text{ mA}$

$I_{tot} = 45\ \mu\text{A} + 421\ \mu\text{A} + 435\ \mu\text{A} + 1.73\text{ mA} = 2.63\text{ mA}$

Power amp quiescent current:

$I_{11} \cong 0$

$I_{12} = \dfrac{15.7\text{ V} - 3(0.7\text{ V})}{1.0\text{ k}\Omega} = \dfrac{13.6\text{ V}}{1.0\text{ k}\Omega} = 13.6\text{ mA}$

$I_{13} = \dfrac{-15\text{ V} - (-0.7\text{ V})}{220\ \Omega} = \dfrac{-14.3\text{ V}}{220\ \Omega} = 65\text{ mA}$

$I_{tot} = 13.6\text{ mA} + 65\text{ mA} = 78.6\text{ mA}$

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 mA + 78.6 mA + 866 mA = 947 mA
Amp. × hrs = 947 mA × 4 hrs = 3.79 Ah

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 39 through 43 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).

39. C_{in} open

40. R_{E2} open

41. Q_1 collector-emitter open

42. D_2 shorted

43. 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.

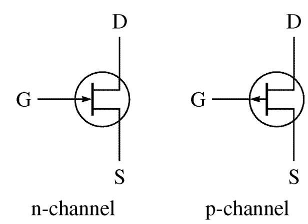


Figure 8-1

4. See Figure 8-2.

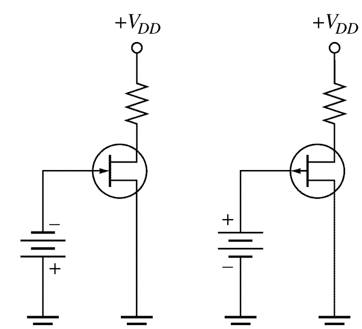


Figure 8-2

Section 8-2 JFET Characteristics and Parameters

5. $V_{DS} = V_P =$ **5 V** at point where I_D becomes constant.

6. $V_{GS(off)} = -V_P =$ **−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, $I_D =$ **10 mA**.

8. Since $V_{GS} > V_{GS(off)}$, the JFET is off and $I_D =$ **0 A**.

9. $V_P = -V_{GS(off)} = -(-4\text{ V}) = 4\text{ V}$
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 $V_{DS} = V_P =$ **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.

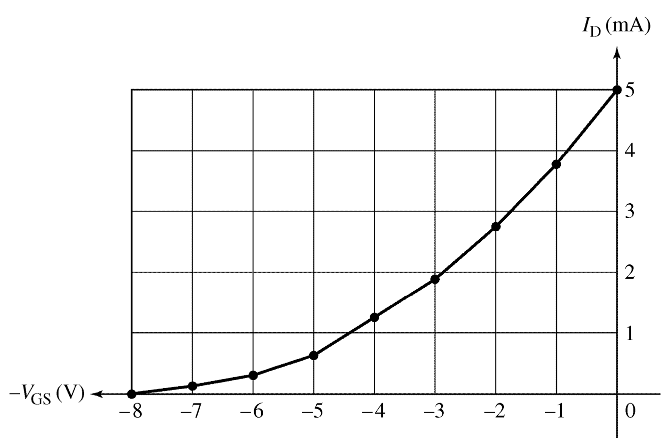


Figure 8-3

11. $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$

$1 - \frac{V_{GS}}{V_{GS(off)}} = \sqrt{\frac{I_D}{I_{DSS}}}$

$\frac{V_{GS}}{V_{GS(off)}} = 1 - \sqrt{\frac{I_D}{I_{DSS}}}$

$V_{GS} = V_{GS(off)}\left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right)$

$V_{GS} = -8\text{ V}\left(1 - \sqrt{\frac{2.25\text{ mA}}{5\text{ mA}}}\right) = -8\text{ V}(0.329) = \mathbf{-2.63\text{ V}}$

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. $g_m = g_{m0}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right) = 2000\ \mu\text{S}\left(1 - \frac{-2\text{ V}}{-7\text{ V}}\right) = \mathbf{1429\ \mu S}$

$g_{fs} = g_m = \mathbf{1429\ \mu S}$

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. $V_{GS} = -I_D R_S = -(12\text{ mA})(100\ \Omega) = -1.2\text{ V}$

17. $R_S = \left|\frac{V_{GS}}{I_D}\right| = \left|\frac{-4\text{ V}}{5\text{ mA}}\right|$ = **800 Ω**

18. $R_S = \left|\frac{V_{GS}}{I_D}\right| = \left|\frac{-3\text{ V}}{2.5\text{ mA}}\right|$ = **1.2 kΩ**

19. (a) $I_D = I_{DSS}$ = **20 mA**
(b) I_D = **0 A**
(c) I_D **increases**

20. (a) V_S = (1 mA)(1.0 kΩ) = 1 V
V_D = 12 V − (1 mA)(4.7 kΩ) = 7.3 V
V_G = 0 V
$V_{GS} = V_G - V_S$ = 0 V − 1 V = **−1 V**
V_{DS} = 7.3 V − 1 V = **6.3 V**

(b) V_S = (5 mA)(100 Ω) = 0.5 V
V_D = 9 V − (5 mA)(470 Ω) = 6.65 V
V_G = 0 V
$V_{GS} = V_G - V_S$ = 0 V − 0.5 V = **−0.5 V**
V_{DS} = 6.65 V − 0.5 V = **6.15 V**

(c) V_S = (−3 mA)(470 Ω) = −1.41 V
V_D = −15 V − (3 mA)(2.2 kΩ) = −8.4 V
V_G = 0 V
$V_{GS} = V_G - V_S$ = 0 V − (−1.41 V) = **1.41 V**
V_{DS} = −8.4 V − (−1.41 V) = **−6.99 V**

21. From the graph, $V_{GS} \cong -2$ V at I_D = 9.5 mA.
$R_S = \left|\frac{V_{GS}}{I_D}\right| = \left|\frac{-2\text{ V}}{9.5\text{ mA}}\right|$ = **211 Ω**

22. $I_D = \frac{I_{DSS}}{2} = \frac{14\text{ mA}}{2}$ = **7 mA**

$V_{GS} = \frac{V_{GS(off)}}{3.414} = \frac{-10\text{ V}}{3.414}$ = **−2.93 V**

$R_S = \left|\frac{V_{GS}}{I_D}\right| = \frac{2.93\text{ V}}{7\text{ mA}}$ = **419 Ω** (The nearest standard value is 430 Ω.)

$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{24\text{ V} - 12\text{ V}}{7\text{ mA}}$ = **1.7 kΩ** (The nearest standard value is 1.8 kΩ.)

Select R_G = 1.0 MΩ. See Figure 8-4.

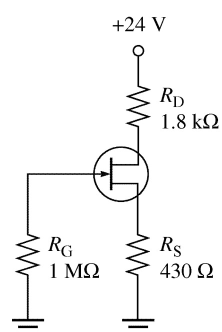


Figure 8-4

23. $R_{IN(total)} = R_G \parallel R_{IN}$

$$R_{IN} = \left|\frac{V_{GS}}{I_{GSS}}\right| = \left|\frac{-10\text{ V}}{20\text{ nA}}\right| = 500\text{ M}\Omega$$

$R_{IN(total)} = 10\text{ M}\Omega \parallel 500\text{ M}\Omega = \mathbf{9.8\text{ M}\Omega}$

24. 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
$V_{GS} \cong$ **−0.95 V** and $I_D \cong$ **2.9 mA**

25. 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
$V_{GS} \cong$ **2.1 V** and $I_D \cong$ **5.3 mA**

26. Since $V_{R_D} = 9\text{ V} - 5\text{ V} = 4\text{ V}$,

$$I_D = \frac{V_{R_D}}{R_D} = \frac{4\text{ V}}{4.7\text{ k}\Omega} = 0.85\text{ mA}$$

$V_S = I_D R_S = (0.85\text{ mA})(3.3\text{ k}\Omega) = 2.81\text{ V}$

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{2.2\text{ M}\Omega}{12.2\text{ M}\Omega}\right)9\text{ V} = 1.62\text{ V}$$

$V_{GS} = V_G - V_S = 1.62\text{ V} - 2.81\text{ V} = -1.19\text{ V}$
Q-point: $I_D =$ **0.85 mA**, $V_{GS} =$ **−1.19 V**

27. 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 $V_{GS} = 0\text{ V}$, $V_S = 4.8\text{ V}$

$$I_D = \frac{V_S}{R_S} = \frac{|V_G - V_{GS}|}{R_S} = \frac{4.8\text{ V}}{3.3\text{ k}\Omega} = 1.45\text{ mA}$$

The Q-point is taken from the graph in Figure 8-72 in the textbook.
$I_D \cong$ **1.9 mA**, $V_{GS} =$ **−1.5 V**

Section 8-4 The Ohmic Region

28. $R_{DS} = \dfrac{V_{DS}}{I_D} = \dfrac{0.8\text{ V}}{0.20\text{ mA}} = \mathbf{4\text{ k}\Omega}$

29. $R_{DS1} = \dfrac{0.4\text{ V}}{0.15\text{ mA}} = 2.67\text{ k}\Omega$

$R_{DS2} = \dfrac{0.6\text{ V}}{0.45\text{ mA}} = 1.33\text{ k}\Omega$

$\Delta R_{DS} = 2.67\text{ k}\Omega - 1.33\text{ k}\Omega = \mathbf{1.34\text{ k}\Omega}$

30. $g_m = g_{m0}\left(1 - \dfrac{V_{GS}}{V_{GS(off)}}\right) = 1.5\text{ mS}\left(1 - \dfrac{-1\text{ V}}{-3.5\text{ V}}\right)$

$= 1.5\text{ mS}(0.714) = \mathbf{1.07\text{ mS}}$

31. $r_{ds} = \dfrac{1}{g_m} = \dfrac{1}{1.07\text{ mS}} = \mathbf{935\ \Omega}$

Section 8-5 The MOSFET

32. See Figure 8-5.

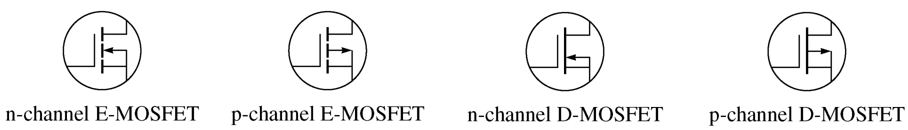


Figure 8-5

33. An *n*-channel D-MOSFET with a positive V_{GS} is operating in the **enhancement mode.**

34. 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.

35. 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

36. $K = \dfrac{I_{D(on)}}{(V_{GS} - V_{GS(th)})^2} = \dfrac{10\text{ mA}}{(-12\text{ V} + 3\text{ V})^2} = 0.12\text{ mA/V}^2$

$I_D = K(V_{GS} - V_{GS(off)})^2 = (0.12\text{ mA/V}^2)(-6\text{ V} + 3\text{ V})^2 = \mathbf{1.08\text{ mA}}$

37. $I_D = I_{DSS}\left(1 - \dfrac{V_{GS}}{V_{GS(off)}}\right)^2$

$I_{DSS} = \dfrac{I_D}{\left(1 - \dfrac{V_{GS}}{V_{GS(off)}}\right)^2} = \dfrac{3\text{ mA}}{\left(1 - \dfrac{-2\text{ V}}{-10\text{ V}}\right)^2} = \mathbf{4.69\text{ mA}}$

38. (a) *n* channel

(b) $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$

$I_D = 8\text{ mA}\left(1 - \frac{-5\text{ V}}{-5\text{ V}}\right)^2$ **= 0 mA**

$I_D = 8\text{ mA}\left(1 - \frac{-4\text{ V}}{-5\text{ V}}\right)^2$ **= 0.32 mA**

$I_D = 8\text{ mA}\left(1 - \frac{-3\text{ V}}{-5\text{ V}}\right)^2$ **= 1.28 mA**

$I_D = 8\text{ mA}\left(1 - \frac{-2\text{ V}}{-5\text{ V}}\right)^2$ **= 2.88 mA**

$I_D = 8\text{ mA}\left(1 - \frac{-1\text{ V}}{-5\text{ V}}\right)^2$ **= 5.12 mA**

$I_D = 8\text{ mA}\left(1 - \frac{0\text{ V}}{-5\text{ V}}\right)^2$ **= 8 mA**

$I_D = 8\text{ mA}\left(1 - \frac{1\text{ V}}{-5\text{ V}}\right)^2$ **= 11.5 mA**

$I_D = 8\text{ mA}\left(1 - \frac{2\text{ V}}{-5\text{ V}}\right)^2$ **= 15.7 mA**

$I_D = 8\text{ mA}\left(1 - \frac{3\text{ V}}{-5\text{ V}}\right)^2$ **= 20.5 mA**

$I_D = 8\text{ mA}\left(1 - \frac{4\text{ V}}{-5\text{ V}}\right)^2$ **= 25.9 mA**

$I_D = 8\text{ mA}\left(1 - \frac{5\text{ V}}{-5\text{ V}}\right)^2$ **= 32 mA**

(c) See Figure 8-6.

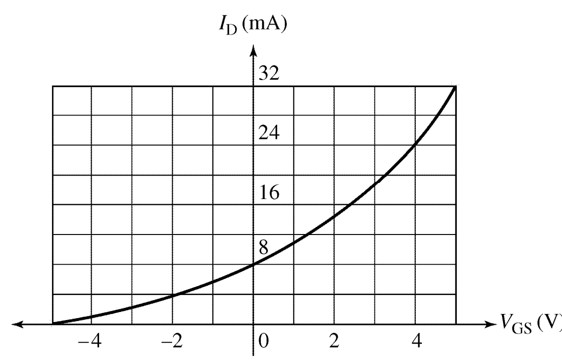


Figure 8-6

Chapter 8

Section 8-7 MOSFET Biasing

39. (a) Depletion
(b) Enhancement
(c) Zero bias
(d) Depletion

40. (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**.

41. Since $V_{GS} = 0$ V for each circuit, $I_D = I_{DSS} = 8$ mA.
(a) $V_{DS} = V_{DD} - I_DR_D = 12\text{ V} - (8\text{ mA})(1.0\text{ k}\Omega) = \mathbf{4\text{ V}}$
(b) $V_{DS} = V_{DD} - I_DR_D = 15\text{ V} - (8\text{ mA})(1.2\text{ k}\Omega) = \mathbf{5.4\text{ V}}$
(c) $V_{DS} = V_{DD} - I_DR_D = -9\text{ V} - (-8\text{ mA})(560\ \Omega) = \mathbf{-4.52\text{ V}}$

42. (a) $I_{D(on)} = 3$ mA @ 4 V, $V_{GS(th)} = 2$ V

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{4.7\text{ M}\Omega}{14.7\text{ M}\Omega}\right)10\text{ V} = \mathbf{3.2\text{ V}}$$

$$K = \frac{I_{D(on)}}{(V_{GS} - V_{GS(th)})^2} = \frac{3\text{ mA}}{(4\text{ V} - 2\text{ V})^2} = \frac{3\text{ mA}}{(2\text{ V})^2} = 0.75\text{ mA/V}^2$$

$I_D = K(V_{GS} - V_{GS(th)})^2 = (0.75\text{ mA/V}^2)(3.2\text{ V} - 2\text{ V})^2 = 1.08$ mA
$V_{DS} = V_{DD} - I_DR_D = 10\text{ V} - (1.08\text{ mA})(1.0\text{ k}\Omega) = 10\text{ V} - 1.08\text{ V} = \mathbf{8.92\text{ V}}$

(b) $I_{D(on)} = 2$ mA @ 3 V, $V_{GS(th)} = 1.5$ V

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{10\text{ M}\Omega}{20\text{ M}\Omega}\right)5\text{ V} = \mathbf{2.5\text{ V}}$$

$$K = \frac{I_{D(on)}}{(V_{GS} - V_{GS(th)})^2} = \frac{2\text{ mA}}{(3\text{ V} - 1.5\text{ V})^2} = \frac{2\text{ mA}}{(1.5\text{ V})^2} = 0.89\text{ mA/V}^2$$

$I_D = K(V_{GS} - V_{GS(th)})^2 = (0.89\text{ mA/V}^2)(2.5\text{ V} - 1.5\text{ V})^2 = 0.89$ mA
$V_{DS} = V_{DD} - I_DR_D = 5\text{ V} - (0.89\text{ mA})(1.5\text{ k}\Omega) = 5\text{ V} - 1.34\text{ V} = \mathbf{3.66\text{ V}}$

43. (a) $V_{DS} = V_{GS} = \mathbf{5\text{ V}}$

$$I_D = \frac{V_{DD} - V_{DS}}{R_D} = \frac{12\text{ V} - 5\text{ V}}{2.2\text{ k}\Omega} = \mathbf{3.18\text{ mA}}$$

(b) $V_{DS} = V_{GS} = \mathbf{3.2\text{ V}}$

$$I_D = \frac{V_{DD} - V_{DS}}{R_D} = \frac{8\text{ V} - 3.2\text{ V}}{4.7\text{ k}\Omega} = \mathbf{1.02\text{ mA}}$$

44. $V_{DS} = V_{DD} - I_DR_D = 15\text{ V} - (1\text{ mA})(8.2\text{ k}\Omega) = 6.8$ V
$V_{GS} = V_{DS} - I_GR_G = 6.8\text{ V} - (50\text{ pA})(22\text{ M}\Omega) = \mathbf{6.799\text{ V}}$

Section 8-8 The IGBT

45. The input resistance of an IGBT is very high because of the insulated gate structure.

46. With excessive collector current, the parasitic transistor turns on and the IGBT acts as a thyristor.

Section 8-9 Troubleshooting

47. 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.

48. If I_D goes to 16 mA, the possible faults are:
The JFET is shorted from drain-to-source or V_{DD} has increased.

49. 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.

50. 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.

51. 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**.

Application Activity Problems

52. (a) −500 mV
(b) −200 mV
(c) 0 mV
(d) 400 mV

53. At $V_{G2S} = 6$ V, $I_D \cong 10$ mA
At $V_{G2S} = 1$ V, $I_D \cong 5$ mA

54. $V_{G1S} = V_{sensor} = -400$ mV
$V_{OUT} = 9.048$ V

$$I_D = \frac{V_{DD} - V_{OUT}}{R_3 + R_4} = \frac{12\text{ V} - 9.048\text{ V}}{1120\ \Omega} = \mathbf{2.64\ mA}$$

$V_{G1S} = V_{sensor} = -300$ mV
$V_{OUT} = 7.574$ V

$$I_D = \frac{12\text{ V} - 7.574\text{ V}}{1120\ \Omega} = \mathbf{3.95\ mA}$$

$V_{G1S} = V_{sensor} = -200$ mV
$V_{OUT} = 5.930$ V

$$I_D = \frac{12\text{ V} - 5.930\text{ V}}{1120\ \Omega} = \mathbf{5.42\ mA}$$

$V_{G1S} = V_{sensor} = -100$ 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
$$I_D = \frac{12\text{ V} - 3.562\text{ V}}{1120\ \Omega} = \mathbf{7.53\ mA}$$

$V_{G1S} = V_{sensor} = 200$ 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 8-7.

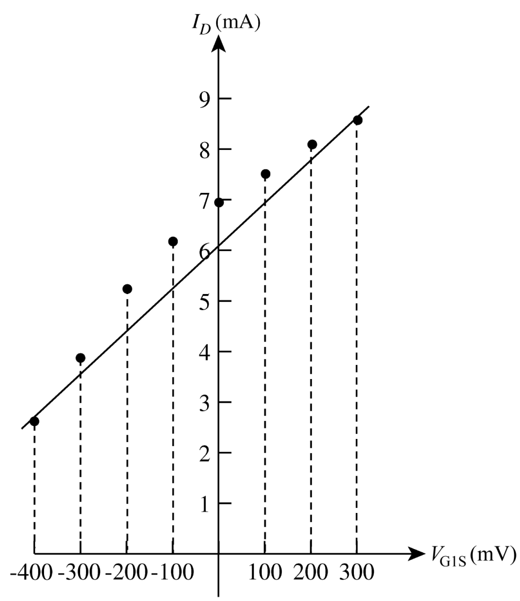


Figure 8-7

55. $$V_{G2S} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{50\text{ k}\Omega}{150\text{ k}\Omega}\right)12\text{ V} = 4\text{ V}$$

From the graph in Figure 8-79 in the textbook for $V_{G1S} = 0$ and $V_{G2S} = 4$ V:
$I_D \cong 8$ mA
$V_{OUT} = 12\text{ V} - (8\text{ mA})(1120\ \Omega) = \mathbf{3.04\ V}$

Datasheet Problems

56. The 2N5457 is an ***n*-channel JFET**.

57. From the datasheet in textbook Figure 8-14:
(a) For a 2N5457, $V_{GS(off)}$ = **−0.5 V** minimum
(b) For a 2N5457, $V_{DS(max)}$ = **25 V**
(c) For a 2N5458 @ 25°C, $P_{D(max)}$ = **310 mW**
(d) For a 2N5459, $V_{GS(rev)}$ = **−25 V** maximum

58. $P_{D(max)}$ = 310 mW − (2.82 mW/°C)(65°C − 25°C) = 310 mW − 113 mW = **197 mW**

59. $g_{m0(min)} = g_{fs}$ = **2000 μS**

60. Typical $I_D = I_{DSS}$ = **9 mA**

61. From the datasheet graph in textbook Figure 8-80:
$I_D \cong$ 1.4 mA at $V_{GS} = 0$

62. For a 2N3796 with V_{GS} = 6 V, I_D = **15 mA**

63. From the datasheet graph in textbook Figure 8-80:
At V_{GS} = +3 V, $I_D \cong$ **13 mA**
At V_{GS} = −2 V, $I_D \cong$ **0.4 mA**

64. y_{fs} = 1500 μS 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.

65. For a 2N3796, $V_{GS(off)}$ = **−3.0 V** typical

Advanced Problems

66. For the circuit of textbook Figure 8-81:

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2 \text{ where } V_{GS} = I_D R_S$$

From the 2N5457 datasheet:
$I_{DSS(min)}$ = 1.0 mA and $V_{GS(off)}$ = −0.5 V minimum
I_D = 66.3 μA
V_{GS} = −(66.3 μA)(5.6 kΩ) = **−0.371 V**
V_{DS} = 12 V − (66.3 μA)(10 kΩ + 5.6 kΩ) = **11.0 V**

67. For the circuit of textbook Figure 8-82:

$V_C = \left(\frac{3.3\,\text{k}\Omega}{13.3\,\text{k}\Omega}\right)9\text{ V} = (0.248)(9\text{ V}) = 2.23\text{ V}$

From the equation,

$I_D = I_{DSS}\left(\frac{V_{GS}}{1 - V_{GS(off)}}\right)^2$ 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**

$V_{GS} = 2.23\text{ V} - (3.58\text{ mA})(1.8\text{ k}\Omega) = 2.23\text{ V} - 6.45\text{ V} =$ **−4.21 V**

68. From the 2N5457 datasheet:

$I_{DSS(min)} = 1.0$ mA and $V_{GS(off)} = -0.5$ minimum

$I_{D(min)} =$ **66.3 μA**

$V_{DS(max)} = 12\text{ V} - (66.3\,\mu\text{A})(15.6\text{ k}\Omega) =$ **11.0 V**

and

$I_{DSS(max)} = 5.0$ mA and $V_{GS(off)} = -6.0$ maximum

$I_{D(max)} =$ **677 μA**

$V_{DS(min)} = 12\text{ V} - (677\,\mu\text{A})(15.6\text{ k}\Omega) =$ **1.4 V**

69. $V_{pH} = +300$ mV

$I_D = (2.9\text{ mA})(1 + 0.3\text{ V}/5.0\text{ V})^2 = (2.9\text{ mA})(1.06)^2 = 3.26\text{ mA}$

$V_{DS} = 15\text{ V} - (3.26\text{ mA})(2.76\text{ k}\Omega) = 15\text{ V} - 8.99\text{ V} =$ **+6.01 V**

70. $1\text{ mA} = I_{DSS}\left(1 - \frac{(1\text{ mA})R_S}{V_{GS(off)}}\right)^2$

$1\text{ mA} = 2.9\text{ mA}\left(1 - \frac{(1\text{ mA})R_S}{-0.5\text{ V}}\right)^2$

$0.345 = \left(1 - \frac{(1\text{ mA})R_S}{-0.5\text{ V}}\right)^2$

$0.587 = 1 - \frac{(1\text{ mA})R_S}{-0.5\text{ V}}$

$0.413 = \frac{(1\text{ mA})R_S}{-0.5\text{ V}}$

$R_S = 2.06\text{ k}\Omega$

Use $R_S =$ **2.2 kΩ**.

Then $I_D = 963\,\mu$A

$V_{GS} = V_S = (963\,\mu\text{A})(2.2\text{ k}\Omega) = 2.19\text{ V}$

So, $V_D = 2.19\text{ V} + 4.5\text{ V} = 6.62\text{ V}$

$R_D = \frac{9\text{ V} - 6.62\text{ V}}{963\,\mu\text{A}} = 2.47\text{ k}\Omega$

Use $R_D =$ **2.4 kΩ**.

So, $V_{DS} = 9\text{ V} - (963\,\mu\text{A})(4.6\text{ k}\Omega) = 4.57\text{ V}$

71. Let $I_D = 20$ mA.

$$R_D = \frac{4\text{ V}}{20\text{ mA}} = \mathbf{200\ \Omega}$$

Let $V_S = 2$ V.

$$R_S = \frac{2\text{ V}}{20\text{ mA}} = \mathbf{100\ \Omega}$$

$$K = \frac{I_{D(on)}}{(V_{GS(on)} - V_{GS(th)})^2} = \frac{500\text{ mA}}{(10\text{ V} - 1\text{ V})^2} = 6.17\text{ mA/V}^2$$

Let $I_D = 20$ mA.

$$(V_{GS} - 1\text{ V})^2 = \frac{20\text{ V}}{6.17\text{ mA/V}^2} = 3.24$$

$V_{GS} - 1\text{ V} = 1.8\text{ V}$

$V_{GS} = 2.8\text{ V}$

$V_G = V_S + 2.8\text{ V} = 4.8\text{ V}$

For the voltage divider:

$$\frac{R_1}{R_2} = \frac{7.2\text{ V}}{4.8\text{ V}} = 1.5$$

Let $R_2 = \mathbf{10\ k\Omega}$.

$R_1 = (1.5)(10\text{ k}\Omega) = \mathbf{15\ k\Omega}$

See Figure 8-8.

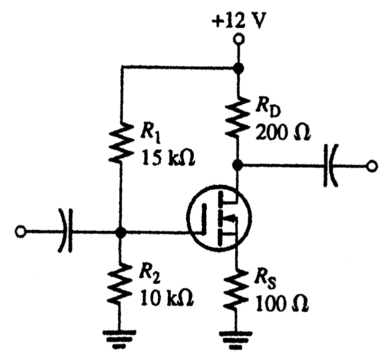


Figure 8-8

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 72 through 80 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).

72. R_S shorted

73. R_D shorted

74. R_G shorted

75. R_1 open

76. Drain-source open

77. R_D open

78. R_2 shorted

79. Drain-source shorted

80. R_1 shorted

Chapter 9
FET Amplifiers and Switching Circuits

Section 9-1 The Common-Source Amplifier

1. (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) $I_d = g_m V_{gs} = (6000\ \mu\text{S})(1\text{ V}) = \mathbf{6\ mA}$

2. $A_v = g_m R_d$

$$R_d = \frac{A_v}{g_m} = \frac{20}{3500\ \mu\text{S}} = \mathbf{5.71\ k\Omega}$$

3. $$A_v = \left(\frac{R_D r'_{ds}}{R_D + r'_{ds}}\right) g_m = \left(\frac{(4.7\text{ k}\Omega)(12\text{ k}\Omega)}{16.7\text{ k}\Omega}\right) 4.2\text{ mS} = \mathbf{14.2}$$

4. $R_d = R_D \parallel r'_{ds} = 4.7\text{ k}\Omega \parallel 12\text{ k}\Omega = 3.38\text{ k}\Omega$

$$A_v = \frac{g_m R_d}{1 + g_m R_s} = \frac{(4.2\text{ mS})(3.38\text{ k}\Omega)}{1 + (4.2\text{ mS})(1.0\text{ k}\Omega)} = \mathbf{2.73}$$

5. (a) *N*-channel D-MOSFET with zero-bias.
$V_{GS} = \mathbf{0\ V}$.
(b) *P*-channel JFET with self-bias.
$V_{GS} = -I_D R_S = (-3\text{ mA})(330\ \Omega) = \mathbf{-0.99\ V}$
(c) *N*-channel E-MOSFET with voltage-divider bias.

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right) V_{DD} = \left(\frac{4.7\text{ k}\Omega}{14.7\text{ k}\Omega}\right) 12\text{ V} = \mathbf{3.84\ V}$$

6. (a) $V_G = \mathbf{0\ V}$, $V_S = \mathbf{0\ V}$
$V_D = V_{DD} - I_D R_D = 15\text{ V} - (8\text{ mA})(1.0\text{ k}\Omega) = \mathbf{7\ V}$

(b) $V_G = \mathbf{0\ V}$
$V_S = -I_D R_D = -(3\text{ mA})(330\ \Omega) = \mathbf{-0.99\ V}$
$V_D = -V_{DD} + I_D R_D = -10\text{ V} + (3\text{ mA})(1.5\text{ k}\Omega) = \mathbf{-5.5\ V}$

(c) $$V_G = \left(\frac{R_2}{R_1 + R_2}\right) V_{DD} = \left(\frac{4.7\text{ k}\Omega}{14.7\text{ k}\Omega}\right) 12\text{ V} = \mathbf{3.84\ V}$$
$V_S = \mathbf{0\ V}$
$V_D = V_{DD} - I_D R_D = 12\text{ V} - (6\text{ mA})(1.0\text{ k}\Omega) = \mathbf{6\ V}$

7. (a) n-channel D-MOSFET
(b) n-channel JFET
(c) p-channel E-MOSFET

8. From the curve in Figure 9-16(a) in the textbook:
$I_{d(pp)} \cong 3.9\text{ mA} - 1.3\text{ mA} = \mathbf{2.6\ mA}$

9. 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:
$I_{d(pp)} \cong 4.5\text{ mA} - 1.3\text{ mA} = \mathbf{3.2\ mA}$

10. $V_D = V_{DD} - I_DR_D = 12\text{ V} - (2.83\text{ mA})(1.5\text{ k}\Omega) = \mathbf{7.76\ V}$
$V_S = I_DR_S = (2.83\text{ mA})(1.0\text{ k}\Omega) = \mathbf{2.83\ V}$
$V_{DS} = V_D - V_S = 7.76\text{ V} - 2.83\text{ V} = \mathbf{4.93\ V}$
$V_{GS} = V_G - V_S = 0\text{ V} - 2.83\text{ V} = \mathbf{-2.83\ V}$

11. $A_v = g_mR_d = g_m(R_D \parallel R_L) = 5000\ \mu\text{S}(1.5\text{ k}\Omega \parallel 10\text{ k}\Omega) = 6.52$
$V_{pp(out)} = (2.828)(50\text{ mV})(6.52) = \mathbf{920\ mV}$

12. $A_v = g_mR_d$
$R_d = 1.5\text{ k}\Omega \parallel 1.5\text{ k}\Omega = 750\ \Omega$
$A_v = (5000\ \mu\text{S})(750\ \Omega) = 3.75$
$V_{out} = A_vV_{in} = (3.75)(50\text{ mV}) = \mathbf{188\ mV\ rms}$

13. (a) $A_v = g_mR_d = g_m(R_D \parallel R_L) = 3.8\text{ mS}(1.2\text{ k}\Omega \parallel 22\text{ k}\Omega) = 3.8\text{ mS}(1138\ \Omega) = \mathbf{4.32}$
(b) $A_v = g_mR_d = g_m(R_D \parallel R_L) = 5.5\text{ mS}(2.2\text{ k}\Omega \parallel 10\text{ k}\Omega) = 5.5\text{ mS}(1.8\text{ k}\Omega) = \mathbf{9.92}$

14. See Figure 9-1.

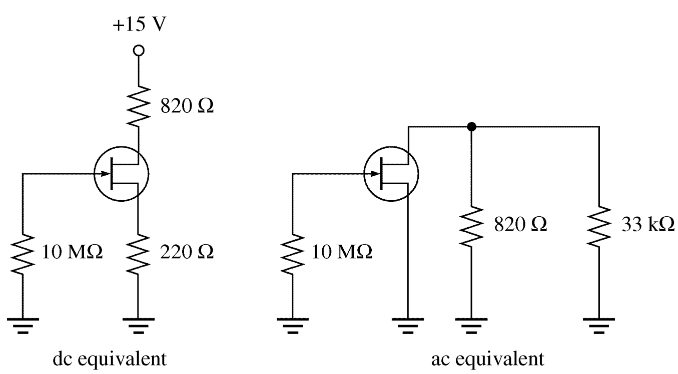


Figure 9-1

15. $I_D = \frac{I_{DSS}}{2} = \frac{15\text{ mA}}{2} = \mathbf{7.5\ mA}$

16. V_{GS} = (7.5 mA)(220 Ω) = 1.65 V

$$g_{m0} = \frac{2I_{DSS}}{|V_{GS(off)}|} = \frac{2(15\text{ mA})}{4\text{ V}} = 7.5\text{ mS}$$

g_m = (7.5 mS)(1 − 1.65 V/4 V) = 4.41 mS

$$A_v = \frac{g_m R_d}{1+g_m R_S} = \frac{(4.41\text{ mS})(820\,\Omega \parallel 3.3\text{ k}\Omega)}{1+(4.41\text{ mS})(220\,\Omega)} = \frac{(4.41\text{ mS})(657\,\Omega)}{1+0.97} = \mathbf{1.47}$$

17. $A_v = g_m R_d = (4.41\text{ mS})(820\,\Omega \parallel 3.3\text{ k}\Omega \parallel 4.7\text{ k}\Omega) = (4.41\text{ mS})(576\,\Omega) = \mathbf{2.54}$

18. $$I_D = \frac{I_{DSS}}{2} = \frac{9\text{ mA}}{2} = \mathbf{4.5\text{ mA}}$$

$V_{GS} = -I_D R_S = -(4.5\text{ mA})(330\,\Omega) = \mathbf{-1.49\text{ V}}$

$V_{DS} = V_{DD} - I_D(R_D + R_S) = 9\text{ V} - (4.5\text{ mA})(1.33\text{ k}\Omega) = \mathbf{3\text{ V}}$

19. $A_v = g_m R_d = g_m(R_D \parallel R_L) = 3700\,\mu\text{S}(1.0\text{ k}\Omega \parallel 10\text{ k}\Omega) = 3700\,\mu\text{S}(909\,\Omega) = 3.36$

$V_{out} = A_v V_{in} = (3.36)(10\text{ mV}) = \mathbf{33.6\text{ mV rms}}$

20. $$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{6.8\text{ k}\Omega}{24.8\text{ k}\Omega}\right)20\text{ V} = \mathbf{5.48\text{ V}}$$

$$K = \frac{I_{D(on)}}{(V_{GS} - V_{GS(th)})^2} = \frac{18\text{ mA}}{(10\text{ V} - 2.5\text{ V})^2} = 0.32\text{ mA/V}^2$$

$I_D = K(V_{GS} - V_{GS(th)})^2 = 0.32\text{ mA/V}^2(5.48\text{ V} - 2.5\text{ V})^2 = \mathbf{2.84\text{ mA}}$

$V_{DS} = V_{DD} - I_D R_D = 20\text{ V} - (2.84\text{ mA})(1.0\text{ k}\Omega) = \mathbf{17.2\text{ V}}$

21. $$R_{IN} = \left|\frac{V_{GS}}{I_{GSS}}\right| = \left|\frac{-15\text{ V}}{25\text{ nA}}\right| = 600\text{ M}\Omega$$

$R_{in} = 10\text{ M}\Omega \parallel 600\text{ M}\Omega = \mathbf{9.84\text{ M}\Omega}$

22. $A_v = g_m R_d = 48\text{ mS}(1.0\text{ k}\Omega \parallel 10\text{ M}\Omega) \cong 4.8$

$V_{out} = A_v V_{in} = 4.8(10\text{ mV}) = \mathbf{48\text{ mV rms}}$

$I_D = I_{DSS} = 15\text{ mA}$

$V_D = 24\text{ V} - (15\text{ mA})(1.0\text{ k}\Omega) = \mathbf{9\text{ V}}$

See Figure 9-2.

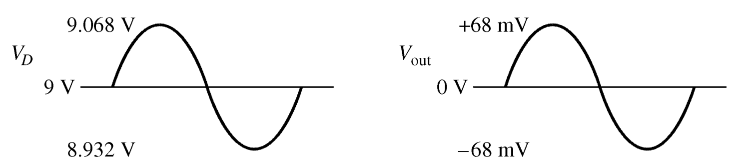


Figure 9-2

23. $V_{GS} = \left(\dfrac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\dfrac{47\text{ k}\Omega}{94\text{ k}\Omega}\right)18\text{ V} = \mathbf{9\ V}$

$K = \dfrac{I_{D(on)}}{(V_{GS} - V_{GS(th)})^2} = \dfrac{8\text{ mA}}{(12\text{ V} - 4\text{ V})^2} = 0.125\text{ mA/V}^2$

$I_{D(on)} = K(V_{GS} - V_{GS(th)})^2 = 0.125\text{ mA/V}^2(9\text{ V} - 4\text{ V})^2 = \mathbf{3.13\ mA}$

$V_{DS} = V_{DD} - I_D R_D = 18\text{ V} - (3.125\text{ mA})(1.5\text{ k}\Omega) = \mathbf{13.3\ V}$

$A_v = g_m R_D = 4500\ \mu\text{S}(1.5\text{ k}\Omega) = 6.75$

$V_{ds} = A_v V_{in} = 6.75(100\text{ mV}) = \mathbf{675\ mV\ rms}$

Section 9-2 The Common-Drain Amplifier

24. $R_s = 1.2\text{ k}\Omega \parallel 1\text{ k}\Omega \cong 545\ \Omega$

$A_v = \dfrac{g_m R_s}{1 + g_m R_s} = \dfrac{(5500\ \mu\text{S})(545\ \Omega)}{1 + (5500\ \mu\text{S})(545\ \Omega)} = \mathbf{0.750}$

$R_{IN} = \left|\dfrac{V_{GS}}{I_{GSS}}\right| = \left|\dfrac{-15\text{ V}}{50\text{ pA}}\right| = 3 \times 10^{11}\ \Omega$

$R_{in} = 10\text{ M}\Omega \parallel 3\times10^{11}\ \Omega \cong \mathbf{10\ M\Omega}$

25. $R_s = 1.2\text{ k}\Omega \parallel 1\text{ k}\Omega \cong 545\ \Omega$

$A_v = \dfrac{g_m R_s}{1 + g_m R_s} = \dfrac{(3000\ \mu\text{S})(545\ \Omega)}{1 + (3000\ \mu\text{S})(545\ \Omega)} = \mathbf{0.620}$

$R_{IN} = \left|\dfrac{V_{GS}}{I_{GSS}}\right| = \left|\dfrac{-15\text{ V}}{50\text{ pA}}\right| = 3 \times 10^{11}\ \Omega$

$R_{in} = 10\text{ M}\Omega \parallel 3\times10^{11}\ \Omega \cong \mathbf{10\ M\Omega}$

26. (a) $R_s = 4.7\text{ k}\Omega \parallel 47\text{ k}\Omega = 4.27\text{ k}\Omega$

$A_v = \dfrac{g_m R_s}{1 + g_m R_s} = \dfrac{(3000\ \mu\text{S})(4.27\text{ k}\Omega)}{1 + (3000\ \mu\text{S})(4.27\text{ k}\Omega)} = \mathbf{0.928}$

(b) $R_s = 1.0\text{ k}\Omega \parallel 100\ \Omega = 90.9\ \Omega$

$A_v = \dfrac{g_m R_s}{1 + g_m R_s} = \dfrac{(4300\ \mu\text{S})(90.9\ \Omega)}{1 + (4300\ \mu\text{S})(90.9\ \Omega)} = \mathbf{0.281}$

27. (a) $R_s = 4.7\text{ k}\Omega \parallel 10\text{ k}\Omega = 3.2\text{ k}\Omega$

$A_v = \dfrac{g_m R_s}{1 + g_m R_s} = \dfrac{(3000\ \mu\text{S})(3.2\text{ k}\Omega)}{1 + (3000\ \mu\text{S})(3.2\text{ k}\Omega)} = \mathbf{0.906}$

(b) $R_s = 100\ \Omega \parallel 10\text{ k}\Omega = 99\ \Omega$

$A_v = \dfrac{g_m R_s}{1 + g_m R_s} = \dfrac{(4300\ \mu\text{S})(99\ \Omega)}{1 + (4300\ \mu\text{S})(99\ \Omega)} = \mathbf{0.299}$

Chapter 9

Section 9-3 The Common-Gate Amplifier

28. $A_v = g_m R_d = 4000\mu\text{S}(1.5\text{ k}\Omega) = \mathbf{6.0}$

29. $R_{in(source)} = \dfrac{1}{g_m} = \dfrac{1}{4000\ \mu\text{S}} = \mathbf{250\ \Omega}$

30. $A_v = g_m R_d = 3500\mu\text{S}(10\text{ k}\Omega) = \mathbf{35}$

$R_{in} = R_S \parallel \left(\dfrac{1}{g_m}\right) = 2.2\text{ k}\Omega \parallel \left(\dfrac{1}{3500\ \mu\text{S}}\right) = \mathbf{253\ \Omega}$

31. $X_L = 2\pi fL = 2\pi(100\text{ MHz})(1.5\text{ mH}) = 943\text{ k}\Omega$

$A_v = g_{m(CG)}X_L = (2800\ \mu\text{S})(943\text{ k}\Omega) = \mathbf{2640}$

$R_{in} = R_3 \parallel \left(\dfrac{V_{GS}}{I_{GSS}}\right) = 15\text{ M}\Omega \parallel \left(\dfrac{15\text{ V}}{2\text{ nA}}\right)$

$= 15\text{ M}\Omega \parallel 500\text{ M}\Omega = \mathbf{14.6\ M\Omega}$

Section 9-4 The Class D Amplifier

32. $A_v = \dfrac{2(9\text{ V})}{5\text{ mV}} = \dfrac{18\text{ V}}{5\text{ mV}} = 3600$

33. $P_{out} = (12\text{ V})(0.35\text{ A}) = 4.2\text{ W}$

$P_{int} = (0.25\text{ V})(0.35\text{ A}) + 140\text{ mW}$

$= 87.5\text{ mW} + 140\text{ mW} = 227.5\text{ mW}$

$\eta = \dfrac{P_{out}}{P_{out} + P_{int}} = \dfrac{4.2\text{ W}}{4.2\text{ W} + 227.5\text{ mW}} = \mathbf{0.95}$

Section 9-5 MOSFET Analog Switching

34. $V_G - V_{p(out)} = V_{GS(Th)}$

$V_{p(out)} = V_G - V_{GS(Th)} = 8\text{ V} - 4\text{ V} = 4\text{ V}$

$V_{pp(in)} = 2\ V_{p(out)} = 2 \times 4\text{ V} = \mathbf{8\ V}$

35. $f_{min} = 2 \times 15\text{ kHz} = \mathbf{30\ kHz}$

36. $R = \dfrac{1}{fC}$

$f = \dfrac{1}{RC} = \dfrac{1}{(10\text{ k}\Omega)(10\text{ pF})} = \mathbf{10\ MHz}$

37. $R = \dfrac{1}{fC} = \dfrac{1}{(25\text{ kHz})(0.001\ \mu\text{F})} = \mathbf{40\ k\Omega}$

Section 9-6 MOSFET Digital Switching

38. $V_{out} = +5$ V when $V_{in} = 0$
$V_{out} = 0$ V when $V_{in} = +5$ V

39. (a) $V_{out} = 3.3$ V (b) $V_{out} = 3.3$ V
(c) $V_{out} = 3.3$ V (d) $V_{out} = 0$ V

40. (a) $V_{out} = 3.3$ V (b) $V_{out} = 0$ V
(c) $V_{out} = 0$ V (d) $V_{out} = 0$ V

41. The MOSFET has lower on-state resistance and can turn off faster.

Section 9-7 Troubleshooting

42. (a) $V_{D1} = V_{DD}$; No signal at Q_1 drain; No output signal
(b) $V_{D1} \cong 0$ V (floating); No signal at Q_1 drain; No output signal
(c) $V_{GS1} = 0$ V; $V_S = 0$ 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) $V_{D2} = V_{DD}$; Correct signal at Q_2 gate; No Q_2 drain signal or output signal

43. (a) $V_{out} = 0$ V if C_1 is open.

(b) $A_{v1} = g_m R_d = 5000\ \mu\text{S}(1.5\ \text{k}\Omega) = 7.5$

$$A_{v2} = \frac{g_m R_d}{1 + g_m R_s} = \frac{7.5}{1 + (5000\ \mu\text{S})(470\ \Omega)} = 2.24$$

$A_v = A_{v1}A_{v2} = (7.5)(2.24) = 16.8$
$V_{out} = A_v V_{in} = (16.8)(10\text{ mV}) = 168$ mV

(c) V_{GS} for Q_2 is 0 V, so $I_D = I_{DSS}$. The output is clipped.

(d) No V_{out} because there is no signal at the Q_2 gate.

Datasheet Problems

44. The 2N3796 FET is an ***n*-channel D-MOSFET**.

45. (a) For a 2N3796, the typical $V_{GS(off)}$ = **−3.0 V**
(b) For a 2N3797, $V_{DS(max)}$ = **20 V**
(c) At $T_A = 25°$C, $P_{D(max)}$ = **200 mW**
(d) For a 2N3797, $V_{GS(max)}$ = **±10 V**

46. $P_D = 200\text{ mW} - (1.14\text{ mW/°C})(55°\text{C} - 25°\text{C})$ = **166 mW**

47. For a 2N3796 with $f = 1$ kHz, g_{m0} = **900 μS** minimum

48. At $V_{GS} = 3.5$ V and $V_{DS} = 10$ V,
$I_{D(min)}$ = **9.0 mA**, $I_{D(typ)}$ = **14 mA**, $I_{D(max)}$ = **18 mA**

49. For a zero-biased 2N3796, $I_{D(typ)}$ = **1.5 mA**

50. $A_{v(\max)} = (1800\ \mu S)(2.2\ k\Omega) = \mathbf{3.96}$

Advanced Problems

51. $R_{d(\min)} = 1.0\ k\Omega \parallel 4\ k\Omega = 800\ \Omega$

$A_{v(\min)} = (2.5\ mS)(800\ \Omega) = \mathbf{2.0}$

$R_{d(\max)} = 1.0\ k\Omega \parallel 10\ k\Omega = 909\ \Omega$

$A_{v(\min)} = (7.5\ mS)(909\ \Omega) = \mathbf{6.82}$

52. $I_{DSS(typ)} = 2.9$ mA

$R_D + R_S = \dfrac{12\ V}{2.9\ mA} = 4.14\ k\Omega$

$\dfrac{1}{g_m} = \dfrac{1}{2300\ \mu S} = 435\ \Omega$

If $R_S = 0\ \Omega$, then $R_D \cong 4\ k\Omega$ (3.9 kΩ standard)

$A_v = (2300\ \mu S)(3.9\ k\Omega) = \mathbf{8.97}$

$V_{DS} = 24\ V - (2.9\ mA)(3.9\ k\Omega) = 24\ V - 11.3\ V = \mathbf{12.7\ V}$

The circuit is a common-source zero-biased amplifier with a drain resistor of 3.9 kΩ.

53. To maintain $V_{DS} = 12$ V for the range of I_{DSS} values:

For $I_{DSS(min)} = 2$ mA

$R_D = \dfrac{12\ V}{2\ mA} = 6\ k\Omega$

For $I_{DSS(max)} = 6$ mA

$R_D = \dfrac{12\ V}{6\ mA} = 2\ k\Omega$

To maintain $A_v = 9$ for the range of $g_m(y_{fs})$ values:

For $g_{m(\min)} = 1500\ \mu S$

$R_D = \dfrac{9}{1500\ \mu S} = 6\ k\Omega$

For $g_{m(\max)} = 3000\ \mu S$

$R_D = \dfrac{9}{3000\ \mu S} = 3\ k\Omega$

A drain resistance consisting of a 2.2 kΩ fixed resistor in series with a 5 kΩ 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 V and $A_v = 9$ over the full range of transistor parameter values. See Figure 9-3.

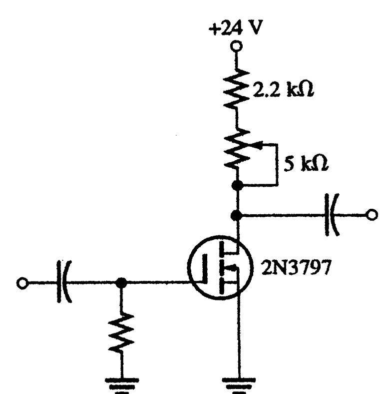


Figure 9-3

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 54 through 62 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).

54. Drain-source shorted

55. C_2 open

56. C_1 open

57. R_S shorted

58. Drain-source open

59. R_1 open

60. R_D open

61. R_2 open

62. C_2 open

Chapter 10
Amplifier Frequency Response

Section 10-1 Basic Concepts

1. If $C_1 = C_2$, the critical frequencies are equal, and they will both cause the gain to decrease at 40 dB/decade below f_c.

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. $V_E \cong \left(\dfrac{R_2}{R_1 + R_2}\right)V_{CC} - 0.7\text{ V} = \left(\dfrac{4.7\text{ k}\Omega}{37.7\text{ k}\Omega}\right)20\text{ V} - 0.7\text{ V} = 1.79\text{ V}$

$I_E = \dfrac{V_E}{R_E} = \dfrac{1.79\text{ V}}{560\,\Omega} = 3.2\text{ mA}$

$r_e' = \dfrac{25\text{ mV}}{3.2\text{ mA}} = 7.8\ \Omega$

$A_v = \dfrac{R_c}{r_e'} = \dfrac{2.2\text{ k}\Omega \parallel 5.6\text{ k}\Omega}{7.8\ \Omega} = 202$

$C_{in(miller)} = C_{bc}(A_v + 1) = 4\text{ pF}(202 + 1) = \mathbf{812\ pF}$

6. $C_{out(miller)} = C_{bc}\left(\dfrac{A_v + 1}{A_v}\right) = 4\text{ pF}\left(\dfrac{203}{202}\right) = \mathbf{4\ pF}$

7. $I_D = 3.36$ mA using Eq. 9−2 and a programmable calculator.
$V_{GS} = -(3.36\text{ mA})(1.0\text{ k}\Omega) = -3.36\text{ V}$

$g_{m0} = \dfrac{2(10\text{ mA})}{8\text{ V}} = 2.5\text{ mS}$

$g_m = (2.5\text{ mS})\left(1 - \dfrac{3.36\text{ V}}{8\text{ V}}\right) = 1.45\text{ mS}$

$A_v = g_m R_d = (1.45\text{ mS})(1.0\text{ k}\Omega \parallel 10\text{ k}\Omega) = 1.32$

$C_{gd} = C_{rss} = 3\text{ pF}$

$C_{in(miller)} = C_{gd}(A_v + 1) = 3\text{ pF}(2.32) = \mathbf{6.95\ pF}$

$C_{out(miller)} = C_{gd}\left(\dfrac{A_v + 1}{A_v}\right) = 3\text{ pF}\left(\dfrac{2.32}{1.32}\right) = \mathbf{5.28\ pF}$

Section 10-2 The Decibel

8. $A_p = \dfrac{P_{out}}{P_{in}} = \dfrac{5\text{ W}}{0.5\text{ W}} = 10$

$A_{p(\text{dB})} = 10\log\left(\dfrac{P_{out}}{P_{in}}\right) = 10\log 10 = \mathbf{10\ dB}$

9. $V_{in} = \dfrac{V_{out}}{A_v} = \dfrac{1.2\text{ V}}{50} = \mathbf{24\ mV\ rms}$

$A_{v(\text{dB})} = 20\log(A_v) = 20\log 50 = \mathbf{34.0\ dB}$

10. The gain reduction is $20\log\left(\dfrac{25}{65}\right) = \mathbf{-8.3\ dB}$

11. (a) $10\log\left(\dfrac{2\text{ mW}}{1\text{ mW}}\right) = \mathbf{3.01\ dBm}$

(b) $10\log\left(\dfrac{1\text{ mW}}{1\text{ mW}}\right) = \mathbf{0\ dBm}$

(c) $10\log\left(\dfrac{4\text{ mW}}{1\text{ mW}}\right) = \mathbf{6.02\ dBm}$

(d) $10\log\left(\dfrac{0.25\text{ mW}}{1\text{ mW}}\right) = \mathbf{-6.02\ dBm}$

12. $V_B = \left(\dfrac{4.7\text{ k}\Omega}{37.7\text{ k}\Omega}\right)20\text{ V} = 1.79\text{ V}$

$I_E = \dfrac{1.79\text{ V}}{560\ \Omega} = 3.20\text{ mA}$

$r_e' = \dfrac{25\text{ mV}}{3.2\text{ mA}} = 7.81\ \Omega$

$A_v = \dfrac{5.6\text{ k}\Omega \parallel 2.2\text{ k}\Omega}{7.81\ \Omega} = 202$

$A_{v(\text{dB})} = 20\log(202) = \mathbf{46.1\ dB}$

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. $R_{IN(BASE)} = \beta_{DC}R_E = 12.5\ k\Omega$

$$V_E = \left(\frac{R_2 \parallel R_{IN(BASE)}}{R_1 + R_2 \parallel R_{IN(BASE)}}\right)9\ V - 0.7\ V = \left(\frac{4.7\ k\Omega \parallel 12.5\ k\Omega}{12\ k\Omega + 4.7\ k\Omega \parallel 12.5\ k\Omega}\right)9\ V - 0.7\ V = 1.3\ V$$

$$I_E = \frac{V_E}{R_E} = \frac{1.3\ V}{100\ \Omega} = 13\ mA$$

$$r_e' = \frac{25\ mV}{13\ mA} = 1.92\ \Omega$$

$$R_{in(base)} = \beta_{ac}r_e' = (125)(1.92\ \Omega) = 240\ \Omega$$

$$R_{in} = 50\ \Omega + R_{in(base)} \parallel R_1 \parallel R_2 = 50\ \Omega + 240\ \Omega \parallel 12\ k\Omega \parallel 4.7\ k\Omega = 274\ \Omega$$

For the input circuit:

$$f_c = \frac{1}{2\pi R_{in}C_1} = \frac{1}{2\pi(274\ \Omega)(1\ \mu F)} = \mathbf{581\ Hz}$$

For the output circuit:

$$f_c = \frac{1}{2\pi(R_C + R_L)C_3} = \frac{1}{2\pi(900\ \Omega)(1\ \mu F)} = \mathbf{177\ Hz}$$

For the bypass circuit:

$$R_{TH} = R_1 \parallel R_2 \parallel R_s = 12\ k\Omega \parallel 4.7\ k\Omega \parallel 50\ \Omega \cong 49.3\ \Omega$$

$$f_c = \frac{1}{2\pi\left(r_e' + R_{TH}/\beta_{DC} \parallel R_E\right)C_2} = \frac{1}{2\pi(2.31\ \Omega)(10\ \mu F)} = \mathbf{6.89\ kHz}$$

$$A_v = \frac{R_C \parallel R_L}{r_e'} = \frac{220\ \Omega \parallel 680\ \Omega}{1.92\ \Omega} = 86.6$$

$A_{v(dB)} = 20\log(86.6) = 38.8$ dB

The **bypass circuit** produces the dominant low critical frequency. See Figure 10-1.

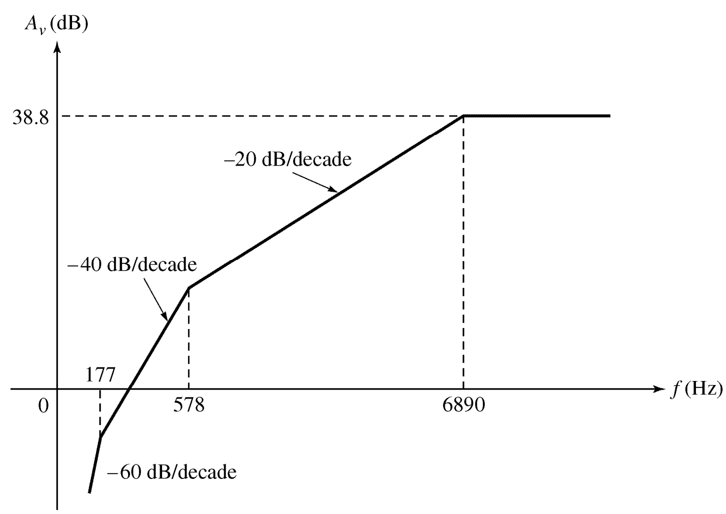


Figure 10-1

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:
$A_v = A_{v(mid)} - 3$ dB = 38.8 dB − 3 dB = **35.8 dB**
At $f = 0.1f_c$:
$A_v = 38.8$ dB − 20 dB = **18.8 dB**
At $10f_c$ (neglecting any high frequency effects):
$A_v = A_{v(mid)}$ = **38.8 dB**

16. At $f = f_c = X_C = R$

$$\theta = \tan^{-1}\left(\frac{X_C}{R}\right) = \tan^{-1}(1) = \mathbf{45°}$$

At $f = 0.1f_c$, $X_C = 10R$.
$\theta = \tan^{-1}(10) = \mathbf{84.3°}$
At $f = 10f_c$, $X_C = 0.1R$.
$\theta = \tan^{-1}(0.1) = \mathbf{5.7°}$

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.)

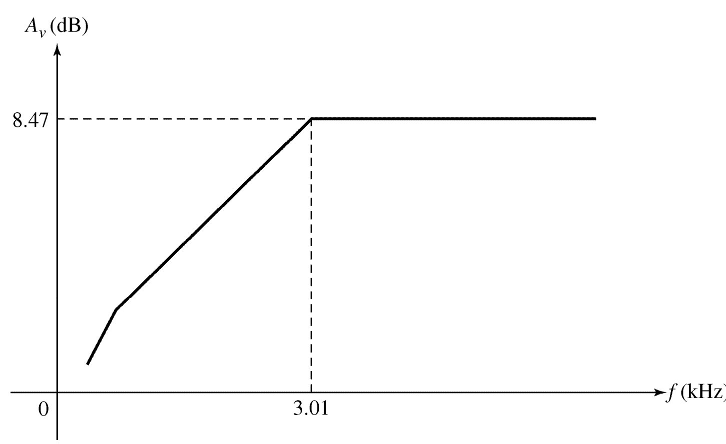


Figure 10-2

18. $g_m = g_{m0} = \dfrac{2(15\text{ mA})}{6\text{ V}} = 5\text{ mS}$

$A_{v(mid)} = g_m(R_D \parallel R_L) = 5\text{ mS}(560\ \Omega \parallel 10\text{ k}\Omega) = 2.65$

$A_{v(mid)}(\text{dB}) = 8.47\text{ dB}$

At f_c:

$A_v = 8.47\text{ dB} - 3\text{ dB} =$ **5.47 dB**

At $0.1f_c$:

$A_v = 8.47\text{ dB} - 20\text{ dB}$ **= −11.5 dB**

At $10f_c$:

$A_v = A_{v(mid)} =$ **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.

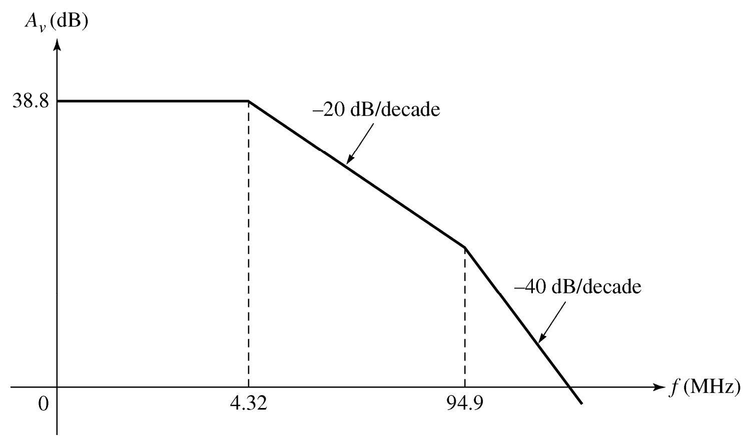


Figure 10-3

20. At $f = 0.1f_c = 458$ kHz:
$A_v = A_{v(mid)} =$ **38.8 dB**
At $f = f_c = 4.58$ MHz:
$A_v = A_{v(mid)} - 3$ dB = 38.8 dB − 3 dB **= 35.8 dB**
At $f = 10f_c = 45.8$ MHz:
$A_v = A_{v(mid)} - 20$ dB = 38.8 dB − 20 dB = **18.8 dB**
At $f = 100f_c = 458$ 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 dB − (0.118)(20 dB) − (0.882)(40 dB) = 18.8 dB − 2.36 dB − 35.3 dB = **−18.9 dB**

21. $C_{gd} = C_{rss} = 4$ pF
$C_{gs} = C_{iss} - C_{rss} = 10$ pF − 4 pF = 6 pF
Input circuit:
$C_{in(miller)} = C_{gd}(A_v + 1) = 4$ pF(2.65 + 1) = 14.6 pF
$C_{tot} = C_{gs} + C_{in(miller)} = 6$ pF + 14.6 pF = 20.6 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 $f = 0.1f_c = 1.29$ MHz: $A_v = A_{v(mid)} =$ **8.47 dB**, $\theta =$ **0°**
At $f = f_c = 12.9$ MHz: $A_v = A_{v(mid)} - 3$ dB = 8.47 dB − 3 dB = **5.47 dB**, $\theta = \tan^{-1}(1) =$ **45°**
At $f = 10f_c = 129$ 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 dB − (0.358)(20 dB) − (0.642)(40 dB) = **−27.4 dB**
At $f = 100f_c = 1290$ MHz: A_v = −27.4 dB − 40 dB = **−67.4 dB**

Chapter 10

Section 10-5 Total Amplifier Frequency Response

23. f_{cl} = **136 Hz**
f_{cu} = **8 kHz**

24. From Problems 14 and 19:
f_{cu} = 4.32 MHz and f_{cl} = 6.89 kHz
$BW = f_{cu} - f_{cl}$ = 4.32 MHz − 6.89 kHz = **4.313 MHz**

25. $f_{tot} = (BW)A_{v(mid)}$

$$BW = \frac{f_{tot}}{A_{v(mid)}} = \frac{200\text{ MHz}}{38} = \mathbf{5.26\text{ MHz}}$$

Therefore, $f_{cu} \cong BW$ = **5.26 MHz**

26. 6 dB/octave roll-off:
At $2f_{cu}$: A_v = 50 dB − 6 dB **= 44 dB**
At $4f_{cu}$: A_v = 50 dB − 12 dB = **38 dB**
20 dB/decade roll-off:
At $10f_{cu}$: A_v = 50 dB − 20 dB = **30 dB**

Section 10-6 Frequency Response of Multistage Amplifiers

27. Dominant f'_{cl} = **230 Hz**
Dominant f'_{cu} = **1.2 MHz**

28. BW = 1.2 MHz − 230 Hz ≅ **1.2 MHz**

29.

$$f'_{cl} = \frac{400\text{ Hz}}{\sqrt{2^{1/2}-1}} = \frac{400\text{ Hz}}{0.643} = 622\text{ Hz}$$

$$f'_{cu} = (800\text{ kHz})\sqrt{2^{1/2}-1} = 0.643(800\text{ kHz}) = 515\text{ kHz}$$

BW = 515 kHz − 622 Hz ≅ **514 kHz**

30.

$$f'_{cl} = \frac{50\text{ Hz}}{\sqrt{2^{1/3}-1}} = \frac{50\text{ Hz}}{0.510} = \mathbf{98.1\text{ Hz}}$$

31.

$$f'_{cl} = \frac{125\text{ Hz}}{\sqrt{2^{1/2}-1}} = \frac{125\text{ Hz}}{0.643} = 194\text{ Hz}$$

f'_{cu} 2.5 MHz
BW = 2.5 MHz − 194 Hz ≅ **2.5 MHz**

Section 10-7 Frequency Response Measurements

32. $f_{cl} = \dfrac{0.35}{t_f} = \dfrac{0.35}{1\text{ ms}}$ = **350 Hz**

$f_{cu} = \dfrac{0.35}{t_r} = \dfrac{0.35}{20\text{ ns}}$ = **17.5 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 kHz − 583 Hz = **22.7 kHz**

Application Activity Problems

35. Q_1 stage:

$$f_{cl(input)} = \frac{1}{2\pi(R_1 \| R_2 \| \beta_{ac} R_4)C_1} = \frac{1}{2\pi(62.3\text{ k}\Omega)1\ \mu\text{F}} = 2.55\text{ Hz}$$

$$f_{cl(bypass)} = \frac{1}{2\pi R_4 C_2} = \frac{1}{2\pi(1\text{ k}\Omega)10\ \mu\text{F}} = 15.9\text{ Hz}$$

$$f_{cl(output)} = \frac{1}{2\pi(R_5 + R_6 \| R_7 \| \beta_{ac}(R_9 + R_{10})C_3} = \frac{1}{2\pi(37\text{ k}\Omega)1\ \mu\text{F}} = 4.30\text{ Hz}$$

Q_2 stage:

$$f_{cl(input)} = \frac{1}{2\pi(R_5 \| R_6 \| R_7 \| \beta_{ac}(R_9 + R_{10})C_3} = \frac{1}{2\pi(8.9\text{ k}\Omega)1\ \mu\text{F}} = 17.9\text{ Hz}$$

$$f_{cl(bypass)} = \frac{1}{2\pi\left(R_9 + \dfrac{R_6 \| R_7}{\beta_{ac}}\right)C_4} = \frac{1}{2\pi(208\ \Omega)100\ \mu\text{F}} = 0.006\text{ Hz}$$

$$f_{cl(output)} = \frac{1}{2\pi(R_8 + R_L)C_5} = \frac{1}{2\pi(35.8\text{ k}\Omega)1\ \mu\text{F}} = 4.45\text{ Hz}$$

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 $I_E = 3.2$ 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.

$$A_v = \frac{R_c}{R_e + r_e'} = 5.13$$

$$R_e = \frac{R_c - 5.13r_e'}{5.13} = \frac{1.58\text{ k}\Omega - 40.1\ \Omega}{5.13} = 300\ \Omega$$

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:

$$f_{cl(in)} = \frac{1}{2\pi R_{in}C_1} = \frac{1}{2\pi(9.52\text{ M}\Omega)(0.005\ \mu\text{F})} = 3.34\text{ Hz}$$

$$f_{cl(out)} = \frac{1}{2\pi(9.52\text{ M}\Omega)(0.005\ \mu\text{F})} = 3.34\text{ Hz since } R_{in(2)} >> 560\ \Omega$$

$$f_{cu(in)} = \frac{1}{2\pi(600\ \Omega)(20.6\text{ pF})} = 12.9\text{ MHz}$$

$$f_{cu(out)} = \frac{1}{2\pi(560\ \Omega)(20.6\text{ pF} + 5.51\text{ pF})} = 10.9\text{ MHz}$$

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 kHz and $f_{cu(in)}$ = 10.9 MHz

$BW \cong$ **10.9 MHz**

44. $R_{in(1)} = 22\text{ k}\Omega \parallel (100)(320\ \Omega) = 13\text{ k}\Omega$

$$V_{B(1)} = \left(\frac{13\text{ k}\Omega}{113\text{ k}\Omega}\right)12\text{ V} = 1.38,\ V_{E(1)} = 0.681\text{ V}$$

$$I_{E(1)} = \frac{0.681\text{ V}}{320\ \Omega} = 2.13\text{ mA},\ r_e' = 11.7\ \Omega$$

$$R_{c(1)} = 4.7\text{ k}\Omega \parallel 33\text{ k}\Omega \parallel 22\text{ k}\Omega \parallel (100)(100\ \Omega) = 2.57\text{ k}\Omega$$

$$A_{v(1)} = \frac{2.57\text{ k}\Omega}{112\ \Omega} = 23$$

$$R_{in(2)} = 22\text{ k}\Omega \parallel (100)(1010\ \Omega) = 18\text{ k}\Omega$$

$$V_{B(2)} = \left(\frac{18\text{ k}\Omega}{51\text{ k}\Omega}\right)12\text{ V} = 4.24,\ V_{E(1)} = 3.54\text{ V}$$

$$I_{E(2)} = \frac{3.54\text{ V}}{1.01\text{ k}\Omega} = 3.51\text{ mA},\ r_e' = 7.13\ \Omega$$

$$R_{c(2)} = 3\text{ k}\Omega \parallel 10\text{ k}\Omega = 2.31\text{ k}\Omega$$

$$A_{v(2)} = \frac{2.31\text{ k}\Omega}{107.13\ \Omega} = 24\text{ maximum}$$

$$A_{v(2)} = \frac{2.31\text{ k}\Omega}{101\text{ k}\Omega + 7.13\ \Omega} = 2.27\text{ minimum}$$

$A_{v(tot)}$ = (23)(24) = 552 maximum
$A_{v(tot)}$ = (23)(2.27) = 52.3 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) = **513** maximum
$A_{v(tot)}$ = (21.3)(2.27) = **48.5** 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 kΩ + 10 kΩ = 13 kΩ

$$f_{cl(out)} = \frac{1}{2\pi(13\,\text{k}\Omega)(10\,\mu\text{F})} = 1.22\text{ Hz}$$

This means that $C_{E(2)}$ is the frequency limiting capacitance.

$$R_{emitter}\ 910\,\Omega \parallel (100\,\Omega + 7\,\Omega + (22\,\text{k}\Omega \parallel 33\,\text{k}\Omega \parallel 3\,\text{k}\Omega)/100) = 115\ \Omega$$

For f'_{cl} = 1 kHz:

$$C_{E(2)} = \frac{1}{2\pi(115\,\Omega)(1\,\text{kHz})} = 1.38\ \mu\text{F}$$

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. $V_A = V_{BE} + V_{CE(sat)} = 0.7\text{ V} + 0.2\text{ V} = 0.9\text{ V}$

$V_{R_S} = V_{BIAS} - V_A = 25\text{ V} - 0.9\text{ V} = 24.1\text{ V}$

$$I_A = \frac{V_{R_S}}{R_S} = \frac{24.1\text{ V}}{1.0\text{ k}\Omega} = \mathbf{24.1\text{ mA}}$$

2. (a) $R_{AK} = \dfrac{V_{AK}}{I_A} = \dfrac{15\text{ V}}{1\,\mu\text{A}} = \mathbf{15\text{ M}\Omega}$

(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,

$$R_{max} = \frac{30\text{ V} - 0.7\text{ V}}{10\text{ mA}} = \mathbf{2.93\text{ k}\Omega}$$

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.

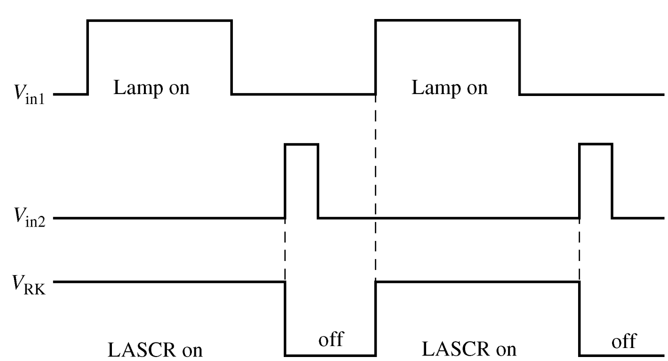


Figure 11-1

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.

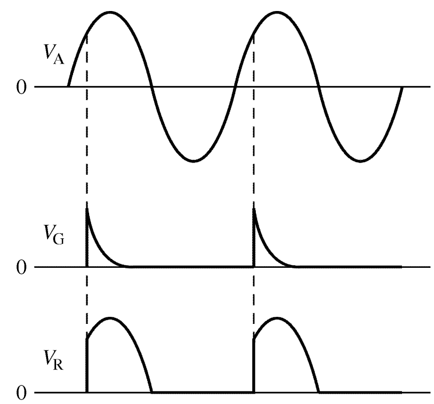


Figure 11-2

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.

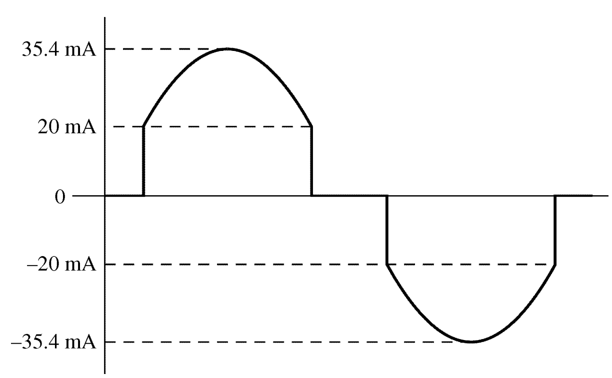


Figure 11-3

11. $I_p = \dfrac{15\text{ V}}{4.7\text{ k}\Omega} = 3.19\text{ mA}$

See Figure 11-4.

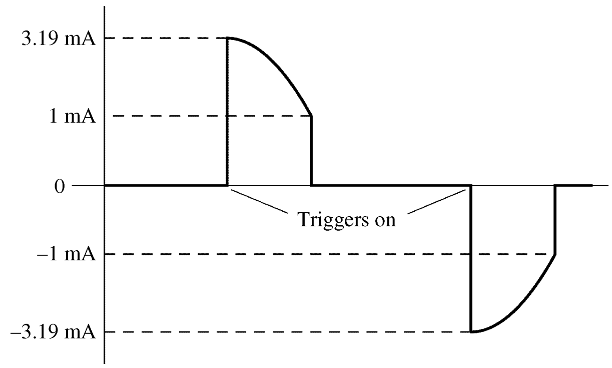


Figure 11-4

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 Unijunction Transistor (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. $V_p = \eta V_{\text{BB}} + V_{pn} = 0.385(15\text{ V}) + 0.7\text{ V} = \mathbf{6.48\ V}$

16. $\dfrac{V_{\text{BB}} - V_v}{I_v} < R_1 < \dfrac{V_{\text{BB}} - V_P}{I_p}$

$\dfrac{12\text{ V} - 0.8\text{ V}}{15\text{ mA}} < R_1 < \dfrac{12\text{ V} - 10\text{ V}}{10\ \mu\text{A}}$

$\mathbf{747\ \Omega < R_1 < 200\ k\Omega}$

Section 11-7 The Programmable UJT (PUT)

17. (a) $V_{\text{A}} = \left(\dfrac{R_3}{R_2 + R_3}\right)V_{\text{B}} + 0.7\text{ V} = \left(\dfrac{10\text{ k}\Omega}{22\text{ k}\Omega}\right)20\text{ V} + 0.7\text{ V} = \mathbf{9.79\ V}$

(b) $V_{\text{A}} = \left(\dfrac{R_3}{R_2 + R_3}\right)V_{\text{B}} + 0.7\text{ V} = \left(\dfrac{47\text{ k}\Omega}{94\text{ k}\Omega}\right)9\text{ V} + 0.7\text{ V} = \mathbf{5.2\ V}$

18. (a) From Problem 17(a), $V_A = 9.79$ V at turn on.

$I = \dfrac{9.79\text{ V}}{470\,\Omega} = 20.8$ mA at turn on

$I_p = \dfrac{10\text{ V}}{470\,\Omega} = 21.3$ mA

See Figure 11-5.

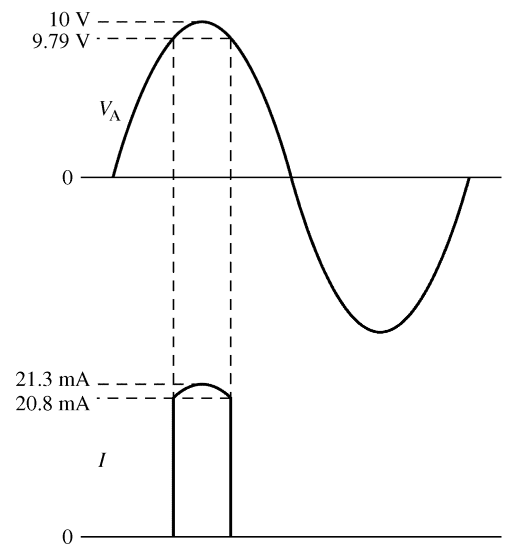


Figure 11-5

(b) From Problem 17(b), $V_A = 5.2$ V at turn on.

$I = \dfrac{5.2\text{ V}}{330\,\Omega} = 15.8$ mA at turn on

$I_p = \dfrac{10\text{ V}}{330\,\Omega} = 30.3$ mA

See Figure 11-6.

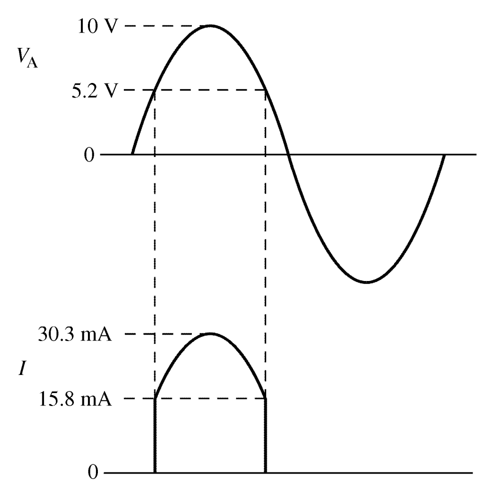


Figure 11-6

19. $V_A = \left(\frac{R_3}{R_2 + R_3}\right)6\text{ V} + 0.7\text{ V} = \left(\frac{10\text{ k}\Omega}{20\text{ k}\Omega}\right)6\text{ V} + 0.7\text{ V} = 3.7\text{ V}$ at turn on

$V_{R1} \cong V_A = 3.7$ V at turn on.
See Figure 11-7.

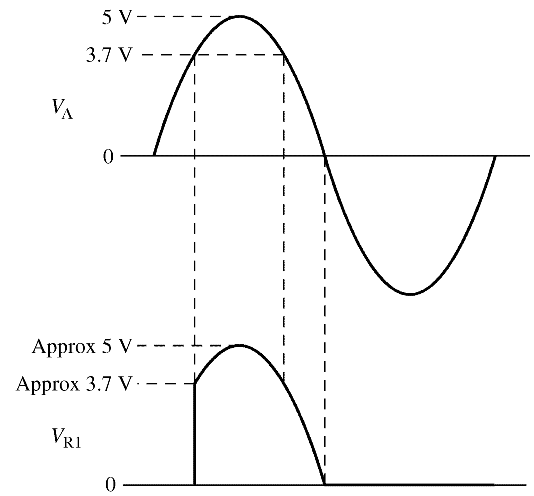


Figure 11-7

20. $V_A = \left(\frac{15\text{ k}\Omega}{25\text{ k}\Omega}\right)6\text{ V} + 0.7\text{ V}$

$= 4.3$ V at turn on
$V_{R1} \cong V_A = 4.3$ V
See Figure 11-8.

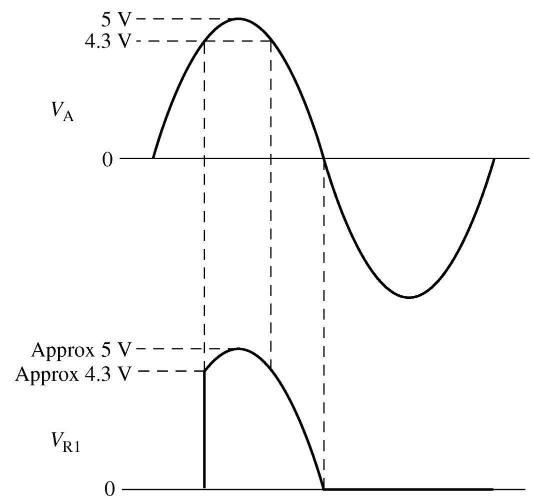


Figure 11-8

Application Activity 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.

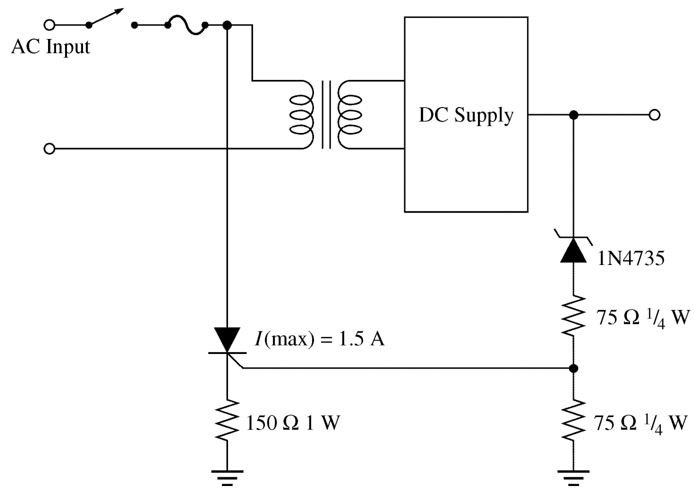


Figure 11-9

26. $V_p = \eta V_{BB} + V_{pn} = (0.75)(12\text{ V}) + 0.7\text{ V} = 9.7\text{ V}$
$I_v = 10\text{ mA}$ 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:

$$V(t) = V_F - (V_F - V_0)e^{-t_1/R_1C}$$

$$9.7\text{ V} = 12\text{ V} - (12\text{ V} - 1\text{ V})e^{-t_1/R_1C}$$

$$-\frac{t_1}{R_1C} = \ln\left(\frac{2.3\text{ V}}{11\text{ V}}\right)$$

$$t_1 = -R_1C\ln\left(\frac{2.3\text{ V}}{11\text{ V}}\right) = 1.56R_1C = 79.8 \times 10^3 C$$

During the discharging cycle (assuming $R_2 >> R_{B1}$):

$V(t) = V_F - (V_F - V_0)e^{-t_2/R_2C}$

$1\text{ V} = 0\text{ V} - (0\text{ V} - 9.3\text{ V})e^{-t_2/R_2C}$

$-\dfrac{t_2}{R_2C} = \ln\left(\dfrac{1\text{ V}}{9.3\text{ V}}\right)$

$t_2 = -R_2C\ln\left(\dfrac{1\text{ V}}{9.3\text{ V}}\right) = 2.23R_2C$

Let $R_2 = 100\text{ k}\Omega$, so $t_2 = 223 \times 10^3C$.

Since $f = 2.5$ kHz, $T = 400\ \mu$s

$T = t_1 + t_2 = 79.8 \times 10^3C + 223 \times 10^3C = 303 \times 10^3C = 400\ \mu$s

$C = \dfrac{400\ \mu\text{s}}{303 \times 10^3} = 0.0013\ \mu$F

See Figure 11-10.

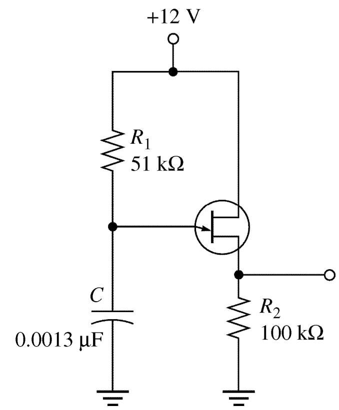


Figure 11-10

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 27 through 29 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).

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.

$I_{\text{OS}} = |8.3\ \mu\text{A} - 7.9\ \mu\text{A}| = \mathbf{400\ nA}$

9. $\text{Slew rate} = \frac{24\ \text{V}}{15\ \mu\text{s}} = \mathbf{1.6\ V/\mu s}$

10. $\Delta t = \frac{\Delta V_{out}}{\text{slew rate}} = \frac{20\ \text{V}}{0.5\ \text{V}/\mu\text{s}} = \mathbf{40\ \mu s}$

Chapter 12

Section 12-4 Op-Amps with Negative Feedback

11. (a) Voltage-follower
(b) Noninverting
(c) Inverting

12. $B = \dfrac{R_i}{R_i + R_f} = \dfrac{1.0\text{ k}\Omega}{101\text{ k}\Omega} = \mathbf{9.90 \times 10^{-3}}$

$V_f = BV_{out} = (9.90 \times 10^{-3})5\text{ V} = 0.0495\text{ V} = \mathbf{49.5\text{ mV}}$

13. (a) $A_{cl(\text{NI})} = \dfrac{1}{B} = \dfrac{1}{1.5\text{ k}\Omega / 561.5\text{ k}\Omega} = \mathbf{374}$

(b) $V_{out} = A_{cl(\text{NI})}V_{in} = (374)(10\text{ mV}) = \mathbf{3.74\text{ V rms}}$

(c) $V_f = \left(\dfrac{1.5\text{ k}\Omega}{561.5\text{ k}\Omega}\right)3.74\text{ V} = \mathbf{9.99\text{ mV rms}}$

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) $1 + \dfrac{R_f}{R_i} = A_{cl(\text{NI})}$

$R_f = R_i(A_{cl(\text{NI})} - 1) = 1.0\text{ k}\Omega(50 - 1) = \mathbf{49\text{ k}\Omega}$

(b) $\dfrac{R_f}{R_i} = A_{cl(\text{I})}$

$R_f = -R_i(A_{cl(\text{I})}) = -10\text{ k}\Omega(-300) = \mathbf{3\text{ M}\Omega}$

(c) $R_f = R_i(A_{cl(\text{NI})} - 1) = 12\text{ k}\Omega(7) = \mathbf{84\text{ k}\Omega}$

(d) $R_f = -R_i(A_{cl(\text{I})}) = -2.2\text{ k}\Omega(-75) = \mathbf{165\text{ k}\Omega}$

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) $V_{out} \cong V_{in}$ = **10 mV, in phase**

(b) $V_{out} = A_{cl}V_{in} = -\left(\frac{R_f}{R_i}\right)V_{in} = -(1)(10\text{ mV}) = \mathbf{-10\ mV,\ 180° \ out\ of\ phase}$

(c) $V_{out} = V_{in} = \left(\frac{1}{\left(\frac{R_1}{R_i + R_f}\right)}\right)V_{in} = \left(\frac{1}{\left(\frac{47\text{ k}\Omega}{1047\text{ k}\Omega}\right)}\right)10\text{ mV} = \mathbf{223\ mV,\ in\ phase}$

(d) $V_{out} = -\left(\frac{R_f}{R_i}\right)V_{in} = -\left(\frac{330\text{ k}\Omega}{33\text{ k}\Omega}\right)10\text{ mV} = \mathbf{-100\ mV,\ 180° \ out\ of\ phase}$

18. (a) $I_{in} = \frac{V_{in}}{R_{in}} = \frac{1\text{ V}}{2.2\text{ k}\Omega} = \mathbf{455\ \mu A}$

(b) $I_f \cong I_{in} = \mathbf{455\ \mu A}$

(c) $V_{out} = -I_fR_f = -(455\ \mu\text{A})(22\text{ k}\Omega) = \mathbf{-10\ V}$

(d) $A_{cl(\text{I})} = -\left(\frac{R_f}{R_i}\right) = -\left(\frac{22\text{ k}\Omega}{2.2\text{ k}\Omega}\right) = \mathbf{-10}$

Section 12-5 Effects of Negative Feedback on Op-Amp Impedances

19. (a) $B = \frac{2.7\text{ k}\Omega}{562.5\text{ k}\Omega} = 0.0048$

$Z_{in(\text{NI})} = (1 + A_{ol})Z_{in} = [1 + (175{,}000)(0.0048)]10\text{ M}\Omega = \mathbf{8.41\ G\Omega}$

$Z_{out(\text{NI})} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{75\ \Omega}{1 + (175{,}000)(0.0048)} = \mathbf{89.2\ m\Omega}$

(b) $B = \frac{1.5\text{ k}\Omega}{48.5\text{ k}\Omega} = 0.031$

$Z_{in(\text{NI})} = (1 + A_{ol}B)Z_{in} = [1 + (200{,}000)(0.031)]1\text{ M}\Omega = \mathbf{6.20\ G\Omega}$

$Z_{out(\text{NI})} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{25\ \Omega}{1 + (200{,}000)(0.031)} = \mathbf{4.04\ m\Omega}$

(c) $B = \frac{56\text{ k}\Omega}{1.056\text{ M}\Omega} = 0.053$

$Z_{in(\text{NI})} = (1 + A_{ol}B)Z_{in} = [1 + (50{,}000)(0.053)]2\text{ M}\Omega = \mathbf{5.30\ G\Omega}$

$Z_{out(\text{NI})} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{50\ \Omega}{1 + (50{,}000)(0.053)} = \mathbf{19.0\ m\Omega}$

20. (a) $Z_{in(\text{VF})} = (1 + A_{ol})Z_{in} = (1 + 220{,}000)6\ \text{M}\Omega = 1.32 \times 10^{12}\ \Omega = \mathbf{1.32\ T\Omega}$

$$Z_{out(\text{VF})} = \frac{Z_{out}}{1 + A_{ol}} = \frac{100\ \Omega}{1 + 220{,}000} = \mathbf{455\ \mu\Omega}$$

(b) $Z_{in(\text{VF})} = (1 + A_{ol})Z_{in} = (1 + 100{,}000)5\ \text{M}\Omega = 5 \times 10^{11}\ \Omega = \mathbf{500\ G\Omega}$

$$Z_{out(\text{VF})} = \frac{Z_{out}}{1 + A_{ol}} = \frac{60\ \Omega}{1 + 100{,}000} = \mathbf{600\ \mu\Omega}$$

(c) $Z_{in(\text{VF})} = (1 + A_{ol})Z_{in} = (1 + 50{,}000)800\ \text{k}\Omega = \mathbf{40\ G\Omega}$

$$Z_{out(\text{VF})} = \frac{Z_{out}}{1 + A_{ol}} = \frac{75\ \Omega}{1 + 500{,}000} = \mathbf{1.5\ m\Omega}$$

21. (a) $Z_{in(\text{I})} \cong R_i = \mathbf{10\ k\Omega}$

$$B = \frac{R_i}{R_i + R_f} = \frac{10\ \text{k}\Omega}{160\ \text{k}\Omega} = 0.0625$$

$$Z_{out(\text{I})} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{40\ \Omega}{1 + (125{,}000)(0.0625)} = \mathbf{5.12\ m\Omega}$$

(b) $Z_{in(\text{I})} \cong R_i = \mathbf{100\ k\Omega}$

$$B = \frac{100\ \text{k}\Omega}{1.1\ \text{M}\Omega} = 0.091$$

$$Z_{out(\text{I})} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{50\ \Omega}{1 + (75{,}000)(0.91)} = \mathbf{7.32\ m\Omega}$$

(c) $Z_{in(\text{I})} \cong R_i = \mathbf{470\ \Omega}$

$$B = \frac{470\ \Omega}{10{,}470\ \Omega} = 0.045$$

$$Z_{out(\text{I})} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{70\ \Omega}{1 + (250{,}000)(0.045)} = \mathbf{6.22\ m\Omega}$$

Section 12-6 Bias Current and Offset Voltage

22. (a) $R_{comp} = R_{in} = \mathbf{75\ \Omega}$ placed in the feedback path.

$I_{\text{OS}} = |42\ \mu\text{A} - 40\ \mu\text{A}| = 2\ \mu\text{A}$

(b) $V_{\text{OUT(error)}} = A_v I_{\text{OS}} R_{in} = (1)(2\ \mu\text{A})(75\ \Omega) = \mathbf{150\ \mu V}$

23. (a) $R_c = R_i \parallel R_f = 2.7\ \text{k}\Omega \parallel 560\ \text{k}\Omega = \mathbf{2.69\ k\Omega}$

(b) $R_c = R_i \parallel R_f = 1.5\ \text{k}\Omega \parallel 47\ \text{k}\Omega = \mathbf{1.45\ k\Omega}$

(c) $R_c = R_i \parallel R_f = 56\ \text{k}\Omega \parallel 1.0\ \text{M}\Omega = \mathbf{53\ k\Omega}$

See Figure 12-1.

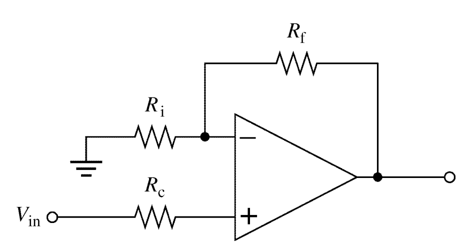


Figure 12-1

24. $V_{OUT(error)} = A_v V_{IO} = (1)(2\text{ nV}) = \mathbf{2\ nV}$

25. $V_{OUT(error)} = (1 + A_{ol})V_{IO}$

$$V_{IO} = \frac{V_{OUT(error)}}{A_{ol}} = \frac{35\text{ mV}}{200{,}000} = \mathbf{175\ nV}$$

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
$A_{v\,(dB)} = 105\text{ dB} - 3\text{ dB} = 102\text{ dB}$

$$A_v = \log^{-1}\left(\frac{102}{20}\right) = \mathbf{125{,}892}$$

$BW_{ol} = \mathbf{200\ Hz}$

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) $A_{ol} = \dfrac{A_{ol(mid)}}{\sqrt{1+\left(\dfrac{f}{f_{c(ol)}}\right)^2}} = \dfrac{80{,}000}{\sqrt{1+\left(\dfrac{100\text{ Hz}}{1\text{ kHz}}\right)^2}}$ **= 79,603**

(b) $A_{ol} = \dfrac{A_{ol(mid)}}{\sqrt{1+\left(\dfrac{f}{f_{c(ol)}}\right)^2}} = \dfrac{80{,}000}{\sqrt{1+\left(\dfrac{1\text{ kHz}}{1\text{ kHz}}\right)^2}}$ **= 56,569**

(c) $A_{ol} = \dfrac{A_{ol(mid)}}{\sqrt{1+\left(\dfrac{f}{f_{c(ol)}}\right)^2}} = \dfrac{80{,}000}{\sqrt{1+\left(\dfrac{10\text{ kHz}}{1\text{ kHz}}\right)^2}}$ **= 7960**

(d) $A_{ol} = \dfrac{A_{ol(mid)}}{\sqrt{1+\left(\dfrac{f}{f_{c(ol)}}\right)^2}} = \dfrac{80{,}000}{\sqrt{1+\left(\dfrac{1\text{ MHz}}{1\text{ kHz}}\right)^2}}$ **= 80**

31. (a) $f_c = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi(10\text{ k}\Omega)(0.01\,\mu\text{F})}$ = 1.59 kHz; $\theta = \tan^{-1}\left(\dfrac{f}{f_c}\right) = \tan^{-1}\left(\dfrac{2\text{ kHz}}{1.59\text{ kHz}}\right)$ **= −51.5°**

(b) $f_c = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi(1.0\text{ k}\Omega)(0.01\,\mu\text{F})}$ = 15.9 kHz; $\theta = \tan^{-1}\left(\dfrac{f}{f_c}\right) = \tan^{-1}\left(\dfrac{2\text{ kHz}}{15.9\text{ kHz}}\right)$ **= −7.17°**

(c) $f_c = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi(100\text{ k}\Omega)(0.01\,\mu\text{F})}$ = 159 Hz; $\theta = \tan^{-1}\left(\dfrac{f}{f_c}\right) = \tan^{-1}\left(\dfrac{2\text{ kHz}}{159\text{ Hz}}\right)$ **= −85.5°**

32. (a) $\theta = \tan^{-1}\left(\dfrac{f}{f_c}\right) = \tan^{-1}\left(\dfrac{100\text{ Hz}}{8.5\text{ kHz}}\right)$ **= −0.674°**

(b) $\theta = \tan^{-1}\left(\dfrac{f}{f_c}\right) = \tan^{-1}\left(\dfrac{400\text{ Hz}}{8.5\text{ kHz}}\right)$ **= −2.69°**

(c) $\theta = \tan^{-1}\left(\dfrac{f}{f_c}\right) = \tan^{-1}\left(\dfrac{850\text{ Hz}}{8.5\text{ kHz}}\right)$ **= −5.71°**

(d) $\theta = \tan^{-1}\left(\dfrac{f}{f_c}\right) = \tan^{-1}\left(\dfrac{8.5\text{ kHz}}{8.5\text{ kHz}}\right)$ **= −45.0°**

(e) $\theta = \tan^{-1}\left(\dfrac{f}{f_c}\right) = \tan^{-1}\left(\dfrac{25\text{ kHz}}{8.5\text{ kHz}}\right)$ **= −71.2°**

(f) $\theta = \tan^{-1}\left(\frac{f}{f_c}\right) = \tan^{-1}\left(\frac{85\text{ kHz}}{8.5\text{ kHz}}\right) = \mathbf{-84.3°}$

See Figure 12-2.

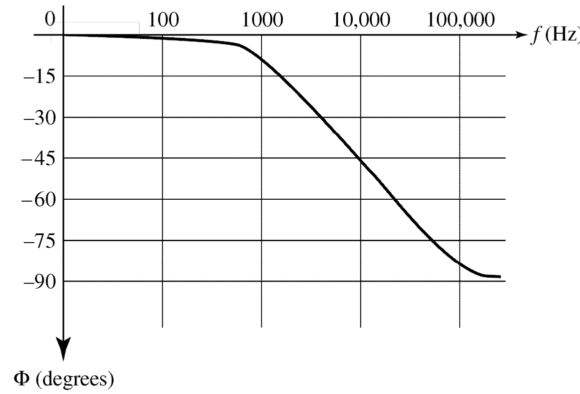


Figure 12-2

33. (a) $A_{ol(mid)}$ = 30 dB + 40 dB + 20 dB = **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) $A_{cl(\text{I})} = -\left(\frac{R_f}{R_i}\right) = -\left(\frac{68\text{ k}\Omega}{2.2\text{ k}\Omega}\right) = -30.9$; $A_{cl(\text{I})}$ (dB) = 20 log(30.9) = **29.8 dB**

(b) $A_{cl(\text{NI})} = \frac{1}{B} = \frac{1}{15\text{ k}\Omega/235\text{ k}\Omega} = 15.7$; $A_{cl(\text{NI})}$ (dB) = 20 log(15.7) = **23.9 dB**

(c) $A_{cl(\text{VF})} = 1$; $A_{cl(\text{VF})}$(dB) = 20 log(1) = **0 dB**
These are all closed-loop gains.

36. $BW_{cl} = BW_{ol}(1 + BA_{ol(mid)})$ = 1500 Hz[1 + (0.015)(180,000)] = **4.05 MHz**

Chapter 12

37. A_{ol} (dB) = 89 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} (dB) = 20 log(3843) = **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 kHz) = **21.1 MHz**

39. (a) $A_{cl(\text{VF})}$ = **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) $$A_{cl} = \frac{150\text{ k}\Omega}{22\text{ k}\Omega} = 6.8$$

$$f_{c(cl)} = \frac{A_{ol}f_{c(ol)}}{A_{cl}} = \frac{(120{,}000)(150\text{ Hz})}{6.8} = 2.65\text{ MHz}$$

$BW = f_{c(cl)}$ = **2.65 MHz**

(b) $$A_{cl} = \frac{1.0\text{ M}\Omega}{10\text{ k}\Omega} = 100$$

$$f_{c(cl)} = \frac{A_{ol}f_{c(ol)}}{A_{cl}} = \frac{(195{,}000)(50\text{ Hz})}{100} = 97.5\text{ kHz}$$

$BW = f_{c(cl)}$ = **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.

Application Activity 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 12-77:

$$B = \frac{470\ \Omega}{47\ \text{k}\Omega + 470\ \Omega} = 0.0099$$

$A_{ol} = 200{,}000$ (typical)
$Z_{in} = 2.0\ \text{M}\Omega$ (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 Figure 12-77:

$$Z_{in(\text{I})} = R_i = \frac{R_f}{A_{cl}} = \frac{100\ \text{k}\Omega}{100} = \mathbf{1\ k\Omega}$$

49. $A_{ol} = 50\ \text{V/mV} = \dfrac{50\ \text{V}}{1\ \text{mV}} = \dfrac{50{,}000\ \text{V}}{1\ \text{V}} = \mathbf{50{,}000}$

50. Slew rate = 0.5 V/μs
$\Delta V = 8\ \text{V} - (-8\ \text{V}) = 16\ \text{V}$

$$\Delta t = \frac{16\ \text{V}}{0.5\ \text{V}/\mu\text{s}} = \mathbf{32\ \mu s}$$

Advanced Problems

51. Using available standard values of $R_f = 150\ \text{k}\Omega$ and $R_i = 1.0\ \text{k}\Omega$,

$$A_v = 1 + \frac{150\ \text{k}\Omega}{1.0\ \text{k}\Omega} = 151$$

$$B = \frac{1.0\ \text{k}\Omega}{151\ \text{k}\Omega} = 6.62 \times 10^{-3}$$

$Z_{in(\text{NI})} = (1 + (6.62 \times 10^{-3})(50{,}000))300\ \text{k}\Omega = 99.6\ \text{M}\Omega$

The compensating resistor is

$R_c = R_i \parallel R_f = 150\ \text{k}\Omega \parallel 1.0\ \text{k}\Omega = 993\ \Omega$

See Figure 12-3.

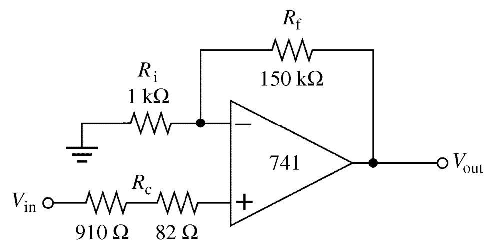


Figure 12-3

52. See Figure 12-4. 2% tolerance resistors are used to achieve a 5% gain tolerance.

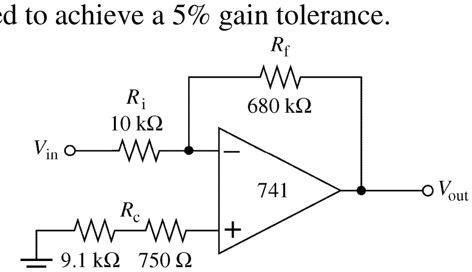


Figure 12-4

53. From textbook Figure 12-78:

$f_c = 10$ 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.

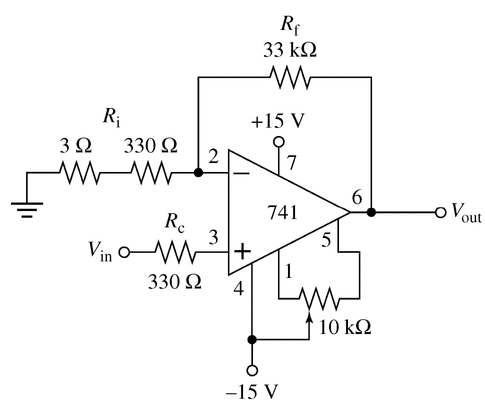


Figure 12-5

54. From textbook Figure 12-79:
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.

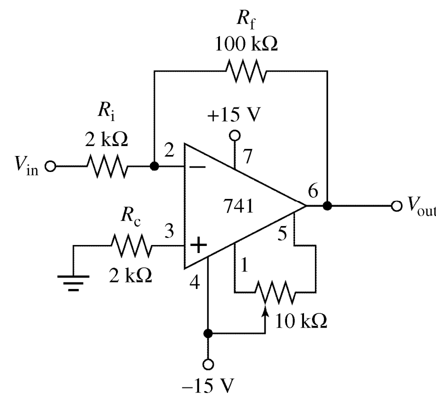


Figure 12-6

56. From textbook Figure 12-78 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

The solutions showing instrument connections for Problems 57 through 72 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).

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

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.
$V_{out(pp)}$ = **24 V 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.

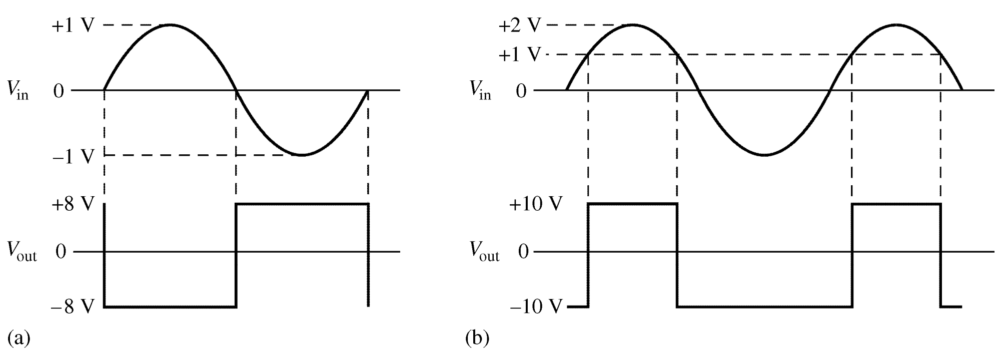


Figure 13-1

6. (a) $V_{UTP} = \left(\frac{R_2}{R_1 + R_2}\right)\left(+V_{out(max)}\right) = \left(\frac{18\text{ k}\Omega}{51\text{ k}\Omega}\right)11\text{ V} = 3.88\text{ V}$

$V_{LTP} = -3.88$ V

$V_{HYS} = V_{UTP} - V_{LTP} = 3.88\text{ V} - (-3.88\text{ V}) = \mathbf{7.76\ V}$

(b) $V_{UTP} = \left(\frac{R_2}{R_1 + R_2}\right)\left(+V_{out(max)}\right) = \left(\frac{68\text{ k}\Omega}{218\text{ k}\Omega}\right)11\text{ V} = 3.43\text{ V}$

$V_{LTP} = -3.43$ V

$V_{HYS} = V_{UTP} - V_{LTP} = 3.43\text{ V} - (-3.43\text{ V}) = \mathbf{6.86\ V}$

7. When the zener is forward-biased:

$V_{out} = \left(\frac{18\text{ k}\Omega}{18\text{ k}\Omega + 47\text{ k}\Omega}\right)V_{out} - 0.7\text{ V}$

$V_{out} = (0.277)V_{out} - 0.7$ V

$V_{out}(1 - 0.277) = -0.7$ V

$V_{out} = \frac{-0.7\text{ V}}{1 - 0.277} = \mathbf{-0.968\ V}$

When the zener is reverse-biased:

$V_{out} = \left(\frac{18\text{ k}\Omega}{18\text{ k}\Omega + 47\text{ k}\Omega}\right)V_{out} + 6.2\text{ V}$

$V_{out} = (0.277)V_{out} + 6.2$ V

$V_{out}(1 - 0.277) = +6.2$ V

$V_{out} = \frac{+6.2\text{ V}}{1 - 0.277} = \mathbf{+8.57\ V}$

8. $V_{out} = \left(\frac{10\text{ k}\Omega}{10\text{ k}\Omega + 47\text{ k}\Omega}\right)V_{out} \pm (4.7\text{ V} + 0.7\text{ V})$

$V_{out} = (0.175)V_{out} \pm 5.4$ V

$V_{out} = \frac{\pm 5.4\text{ V}}{1 - 0.175} = \pm 6.55\text{ V}$

$V_{UTP} = (0.175)(+6.55\text{ V}) = +1.15\text{ V}$

$V_{LTP} = (0.175)(-6.55\text{ V}) = -1.15\text{ V}$

See Figure 13-2.

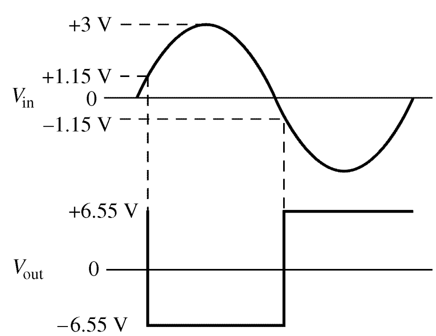


Figure 13-2

Section 13-2 Summing Amplifiers

9. (a) $V_{OUT} = -\frac{R_f}{R_i}(+1\text{ V} + 1.5\text{ V}) = -1(1\text{ V} + 1.5\text{ V}) = \mathbf{-2.5\text{ V}}$

(b) $V_{OUT} = -\frac{R_f}{R_i}(0.1\text{ V} + 1\text{ V} + 0.5\text{ V}) = -\frac{22\text{ k}\Omega}{10\text{ k}\Omega}(1.6\text{ V}) = \mathbf{-3.52\text{ V}}$

10. (a) $V_{R1} = \mathbf{1\text{ V}}$
$V_{R2} = \mathbf{1.8\text{ V}}$

(b) $I_{R1} = \frac{1\text{ V}}{22\text{ k}\Omega} = 45.5\ \mu\text{A}$

$I_{R2} = \frac{1.8\text{ V}}{22\text{ k}\Omega} = 81.8\ \mu\text{A}$

$I_f = I_{R1} + I_{R2} = 45.5\ \mu\text{A} + 81.8\ \mu\text{A} = \mathbf{127\ \mu A}$

(c) $V_{OUT} = -I_f R_f = -(127\ \mu\text{A})(22\text{ k}\Omega) = \mathbf{-2.8\text{ V}}$

11. $5V_{in} = \left(\frac{R_f}{R}\right)V_{in}$

$\frac{R_f}{R} = 5$

$R_f = 5R = 5(22\text{ k}\Omega) = \mathbf{110\text{ k}\Omega}$

12. See Figure 13-3.

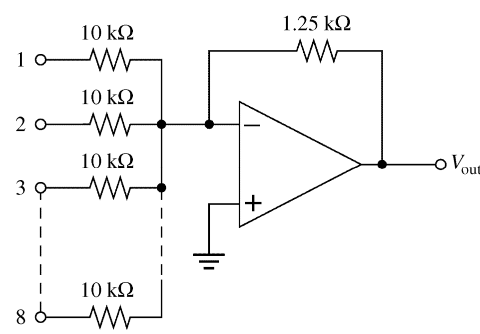


Figure 13-3

13. $V_{OUT} = -\left[\left(\frac{R_f}{R_1}\right)V_1 + \left(\frac{R_f}{R_2}\right)V_2 + \left(\frac{R_f}{R_3}\right)V_3 + \left(\frac{R_f}{R_4}\right)V_4\right]$

$= -\left[\left(\frac{10\text{ k}\Omega}{10\text{ k}\Omega}\right)2\text{ V} + \left(\frac{10\text{ k}\Omega}{33\text{ k}\Omega}\right)3\text{ V} + \left(\frac{10\text{ k}\Omega}{91\text{ k}\Omega}\right)3\text{ V} + \left(\frac{10\text{ k}\Omega}{180\text{ k}\Omega}\right)6\text{ V}\right]$

$= -(2\text{ V} + 0.91\text{ V} + 0.33\text{ V} + 0.33\text{ V}) = \mathbf{-3.57\text{ V}}$

$I_f = \frac{V_{OUT}}{R_f} = \frac{3.57\text{ V}}{10\text{ k}\Omega} = \mathbf{357\ \mu A}$

14. R_f = **100 kΩ**
Input resistors: R_1 = **100 kΩ**, R_2 = **50 kΩ**, R_3 = **25 kΩ**, R_4 = **12.5 kΩ,**
R_5 = **6.25 kΩ**, R_6 = **3.125 kΩ**

Section 13-3 Integrators and Differentiators

15. $\frac{dV_{out}}{dt} = -\frac{V_{IN}}{RC} = -\frac{5\text{ V}}{(56\text{ k}\Omega)(0.022\ \mu\text{F})}$ $= \mathbf{-4.06\ mV/\mu s}$

16. See Figure 13-4.

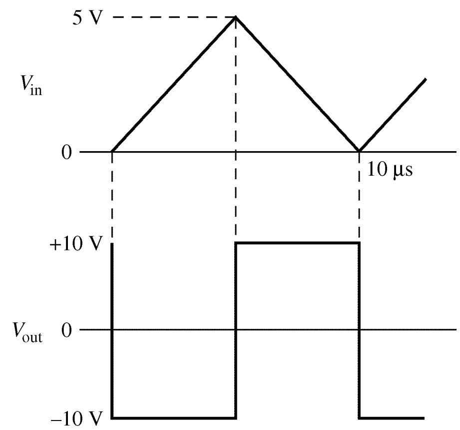


Figure 13-4

17. $I = \frac{CV_{pp}}{T/2} = \frac{(0.001\ \mu\text{F})(5\text{ V})}{10\ \mu s/2}$ $= \mathbf{1\ mA}$

18. $V_{out} = \pm RC\left(\frac{V_{pp}}{T/2}\right) = \pm(15\text{ k}\Omega)(0.047\ \mu\text{F})\left(\frac{2\text{ V}}{0.5\text{ ms}}\right)$ $= \mathbf{\pm 2.82\ V}$

See Figure 13-5.

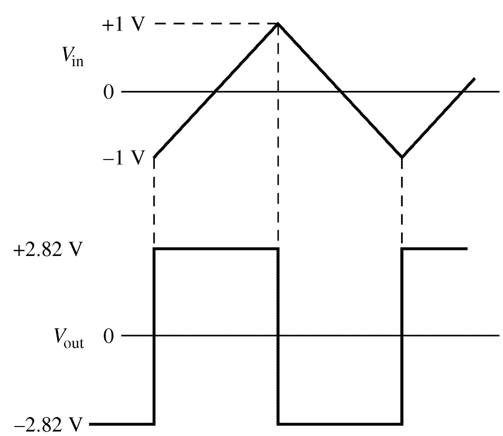


Figure 13-5

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.

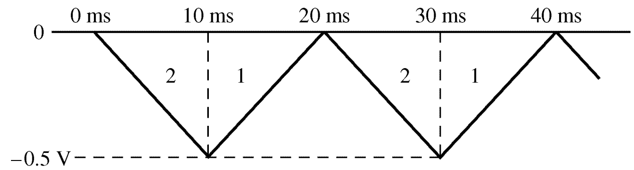


Figure 13-6

Section 13-4 Troubleshooting

20.

$$V_B = \left(\frac{R_2}{R_1 + R_2}\right)V_{out} \pm (V_Z + 0.7\text{ V})$$

$$V_B = \frac{\pm (V_Z + 0.7\text{ V})}{1 - \left(\frac{R_2}{R_1 + R_2}\right)}$$

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 $\boldsymbol{D_2}$ **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 $\boldsymbol{R_2}$ **is open**.

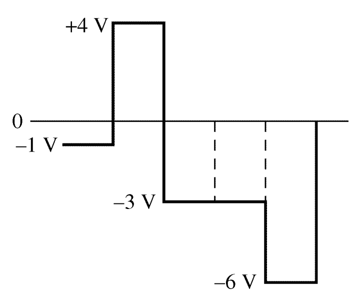


Figure 13-7

22. $A_v = \dfrac{2.5\ \text{k}\Omega}{10\ \text{k}\Omega} = 0.25$

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.

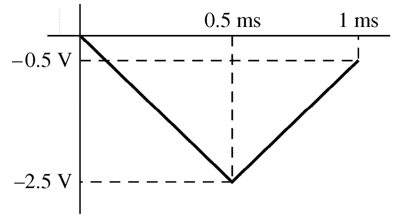


Figure 13-8

23. The D_2 input is missing (acts as a constant 0). This indicates an **open 50 kΩ resistor**.

Application Activity 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. $I_{R1\text{-}2\text{-}3} = \dfrac{24\ \text{V}}{612\ \text{k}\Omega} = 39.2\ \mu\text{A}$

Minimum setting of R_2:

$V_{\text{INV}} = 12\ \text{V} - (39.2\ \mu\text{A})(56\ \text{k}\Omega) = 9.8\ \text{V}$

$v = V_p \sin\theta$

$\sin\theta = \dfrac{v}{V_p} = \dfrac{9.8\ \text{V}}{10\ \text{V}} = 0.98$

$$\theta = \sin^{-1}\left(\frac{v}{V_p}\right) = \sin^{-1}(0.98) = 78.5° \text{ (on positive half cycle)}$$

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

$\theta = 11.5° + 11.5° = 23°$

$$\text{min. duty cycle} = \left(\frac{23°}{360°}\right)100 = \mathbf{6.39\%}$$

See Figure 13-9(a).

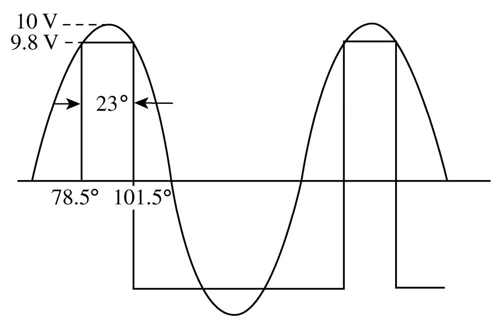
Maximum setting of R_2:

$V_{INV} = 12\text{ V} - (39.2\ \mu\text{A})(556\text{ k}\Omega) = -9.8\text{ V}$

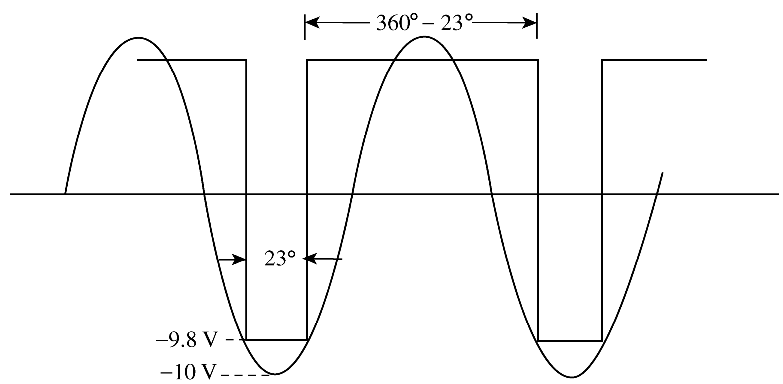
$$\sin\theta = \frac{v}{V_p} = \frac{-9.8\text{ V}}{10\text{ V}} = -78.5° \text{ (on negative half cycle)}$$

$$\text{max. duty cycle} = \left(\frac{360° - 23°}{360°}\right)100 = \mathbf{93.6\%}$$

See Figure 13-9(b).



(a)



(b)

Figure 13-9

28. Let $V_{INV} = 4.8$ V

Let $I_1 = 39.2\ \mu$A

$V_{INV} = 12\text{ V} - I_1R_1$

$-I_1R_1 = 4.8\text{ V} - 12\text{ V}$

$I_1R_1 = 7.2$ 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 kΩ.

29. 100 mV/μs = 5 V/R_iC

$$R_iC = \frac{5\text{ V}}{100\text{ mV}/\mu\text{s}} = 50\ \mu\text{s}$$

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:

$$t_{ramp\ up} = t_{ramp\ down} = \frac{5\text{ V}}{100\text{ mV}/\mu\text{s}} = 50\ \mu\text{s}$$

τ = 2(50 μs) = 100 μs

f_{in} = 1/100 μs = **100 kHz**

See Figure 13-10.

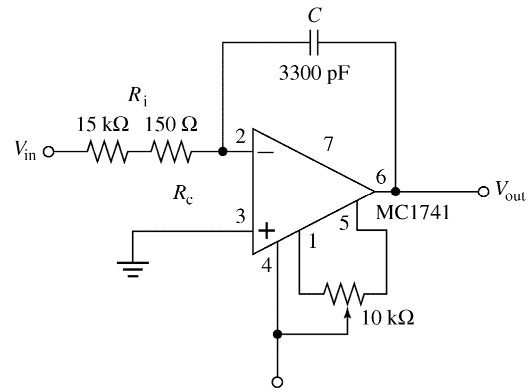


Figure 13-10

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 30 through 39 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).

30. R_1 open

31. Op-amp inputs shorted together

32. Op-amp + input to output shorted

33. D_1 shorted

34. Top 10 kΩ resistor open

35. Middle 10 kΩ resistor shorted

36. R_f leaky

37. R_f open

38. C leaky

39. C open

Chapter 14
Special-Purpose Op-Amp Circuits

Section 14-1 Instrumentation Amplifiers

1. $A_{v(1)} = 1 + \dfrac{R_1}{R_G} = 1 + \dfrac{100\text{ k}\Omega}{1.0\text{ k}\Omega} = \mathbf{101}$

$A_{v(2)} = 1 + \dfrac{R_2}{R_G} = 1 + \dfrac{100\text{ k}\Omega}{1.0\text{ k}\Omega} = \mathbf{101}$

2. $A_{cl} = 1 + \dfrac{2R}{R_G} = 1 + \dfrac{200\text{ k}\Omega}{1.0\text{ k}\Omega} = \mathbf{201}$

3. $V_{out} = A_{cl}(V_{in(2)} - V_{in(1)}) = 202(10\text{ mV} - 5\text{ mV}) = \mathbf{1.005\ V}$

4. $A_v = 1 + \dfrac{2R}{R_G}$

$\dfrac{2R}{R_G} = A_v - 1$

$R_G = \dfrac{2R}{A_v - 1} = \dfrac{2(100\text{ k}\Omega)}{1000 - 1} = \dfrac{200\text{ k}\Omega}{999} = 200.2\ \Omega \cong \mathbf{200\ \Omega}$

5. $R_G = \dfrac{50.5\text{ k}\Omega}{A_v - 1}$

$A_v = \dfrac{50.5\text{ k}\Omega}{1.0\text{ k}\Omega} + 1 = \mathbf{51.5}$

6. Using the graph in textbook Figure 14-6,
$BW \cong$ **300 kHz**

7. Change R_G to
$R_G = \dfrac{50.5\text{ k}\Omega}{A_v - 1} = \dfrac{50.5\text{ k}\Omega}{24 - 1} \cong \mathbf{2.2\ k\Omega}$

8. $R_G = \dfrac{50.5\text{ k}\Omega}{A_v - 1} = \dfrac{50.5\text{ k}\Omega}{20 - 1} \cong \mathbf{2.7\ k\Omega}$

Chapter 14

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) $A_{v1} = \dfrac{R_{f1}}{R_{i1}} + 1 = \dfrac{330\text{ k}\Omega}{1.0\text{ k}\Omega} + 1 = 331$

$A_{v2} = \dfrac{R_{f2}}{R_{i2}} + 1 = \dfrac{47\text{ k}\Omega}{15\text{ k}\Omega} + 1 = 4.13$

$A_{v(tot)} = A_{v1}A_{v2} = (331)(4.13) = \mathbf{1{,}367}$

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** ± 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 $R_f = 0$.

Section 14-3 Operational Transconductance Amplifiers (OTAs)

14. $g_m = \dfrac{I_{out}}{V_{in}} = \dfrac{10\ \mu\text{A}}{10\text{ mV}} = \mathbf{1\ mS}$

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. $g_m = \dfrac{I_{out}}{V_{in}}$

$I_{out} = g_m V_{in} = (4000\ \mu\text{S})(100\ \text{mV}) = 400\ \mu\text{A}$

$R_L = \dfrac{V_{out}}{I_{out}} = \dfrac{3.5\ \text{V}}{400\ \mu\text{A}}$ = $\mathbf{8.75\ k\Omega}$

17. $I_{\text{BIAS}} = \dfrac{+12\ \text{V} - (-12\ \text{V}) - 0.7\ \text{V}}{R_{\text{BIAS}}} = \dfrac{+12\ \text{V} - (-12\ \text{V}) - 0.7\ \text{V}}{220\ \text{k}\Omega} = \dfrac{23.3\ \text{V}}{220\ \text{k}\Omega} = 106\ \mu\text{A}$

From the graph in Figure 14-57:

$g_m = KI_{\text{BIAS}} \cong (16\ \mu\text{S}/\mu\text{A})(106\ \mu\text{A}) = 1.70\ \text{mS}$

$A_v = \dfrac{V_{out}}{V_{in}} = \dfrac{I_{out}R_L}{V_{in}} = g_m R_L = (1.70\ \text{mS})(6.8\ \text{k}\Omega) = \mathbf{11.6}$

18. The maximum voltage gain occurs when the 10 kΩ potentiometer is set to 0 Ω and was determined in Problem 17.

$A_{v(max)} = \mathbf{11.6}$

The minimum voltage gain occurs when the 10 kΩ potentiometer is set to 10 kΩ.

$I_{\text{BIAS}} = \dfrac{+12\ \text{V} - (-12\ \text{V}) - 0.7\ \text{V}}{220\ \text{k}\Omega + 10\ \text{k}\Omega} = \dfrac{23.3\ \text{V}}{230\ \text{k}\Omega} = 101\ \mu\text{A}$

$g_m \cong (16\ \mu\text{S}/\mu\text{A})(101\ \mu\text{A}) = 1.62\ \text{mS}$

$A_{v(min)} = g_m R_L = (1.62\ \text{mS})(6.8\ \text{k}\Omega) = \mathbf{11.0}$

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 $V_{\text{MOD}} = +8$ V:

$I_{\text{BIAS}} = \dfrac{+8\ \text{V} - (-9\ \text{V}) - 0.7\ \text{V}}{39\ \text{k}\Omega} = \dfrac{16.3\ \text{V}}{39\ \text{k}\Omega} = 418\ \mu\text{A}$

$g_m = KI_{\text{BIAS}} \cong (16\ \mu\text{S}/\mu\text{A})(418\ \mu\text{A}) = 6.69\ \text{mS}$

$A_v = \dfrac{V_{out}}{V_{in}} = \dfrac{I_{out}R_L}{V_{in}} = g_m R_L = (6.69\ \text{mS})(10\ \text{k}\Omega) = 66.9$

$V_{out} = A_v V_{in} = (66.9)(100\ \text{mV}) = \mathbf{6.69\ V}$

For $V_{\text{MOD}} = +6$ V:

$I_{\text{BIAS}} = \dfrac{+6\ \text{V} - (-9\ \text{V}) - 0.7\ \text{V}}{39\ \text{k}\Omega} = \dfrac{14.3\ \text{V}}{39\ \text{k}\Omega} = 367\ \mu\text{A}$

$g_m = KI_{\text{BIAS}} \cong (16\ \mu\text{S}/\mu\text{A})(367\ \mu\text{A}) = 5.87\ \text{mS}$

$A_v = \dfrac{V_{out}}{V_{in}} = \dfrac{I_{out}R_L}{V_{in}} = g_m R_L = (5.87\ \text{mS})(10\ \text{k}\Omega) = 58.7$

$V_{out} = A_v V_{in} = (58.7)(100\ \text{mV}) = \mathbf{5.87\ V}$

For $V_{MOD} = +4$ V:

$$I_{BIAS} = \frac{+4\text{ V} - (-9\text{ V}) - 0.7\text{ V}}{39\text{ k}\Omega} = \frac{12.3\text{ V}}{39\text{ k}\Omega} = 315\ \mu\text{A}$$

$g_m = KI_{BIAS} \cong (16\ \mu\text{S}/\mu\text{A})(315\ \mu\text{A}) = 5.04$ mS

$$A_v = \frac{V_{out}}{V_{in}} = \frac{I_{out}R_L}{V_{in}} = g_mR_L = (5.04\text{ mS})(10\text{ k}\Omega) = 50.4$$

$V_{out} = A_vV_{in} = (50.4)(100\text{ mV}) = \mathbf{5.04\ V}$

For $V_{MOD} = +2$ V:

$$I_{BIAS} = \frac{+2\text{ V} - (-9\text{ V}) - 0.7\text{ V}}{39\text{ k}\Omega} = \frac{10.3\text{ V}}{39\text{ k}\Omega} = 264\ \mu\text{A}$$

$g_m = KI_{BIAS} \cong (16\ \mu\text{S}/\mu\text{A})(264\ \mu\text{A}) = 4.22$ mS

$$A_v = \frac{V_{out}}{V_{in}} = \frac{I_{out}R_L}{V_{in}} = g_mR_L = (4.22\text{ mS})(10\text{ k}\Omega) = 42.2$$

$V_{out} = A_vV_{in} = (42.2)(100\text{ mV}) = \mathbf{4.22\ V}$

For $V_{MOD} = +1$ V:

$$I_{BIAS} = \frac{+1\text{ V} - (-9\text{ V}) - 0.7\text{ V}}{39\text{ k}\Omega} = \frac{9.3\text{ V}}{39\text{ k}\Omega} = 238\ \mu\text{A}$$

$g_m = KI_{BIAS} \cong (16\ \mu\text{S}/\mu\text{A})(238\ \mu\text{A}) = 3.81$ mS

$$A_v = \frac{V_{out}}{V_{in}} = \frac{I_{out}R_L}{V_{in}} = g_mR_L = (3.81\text{ mS})(10\text{ k}\Omega) = 38.1$$

$V_{out} = A_vV_{in} = (38.1)(100\text{ mV}) = \mathbf{3.81\ V}$

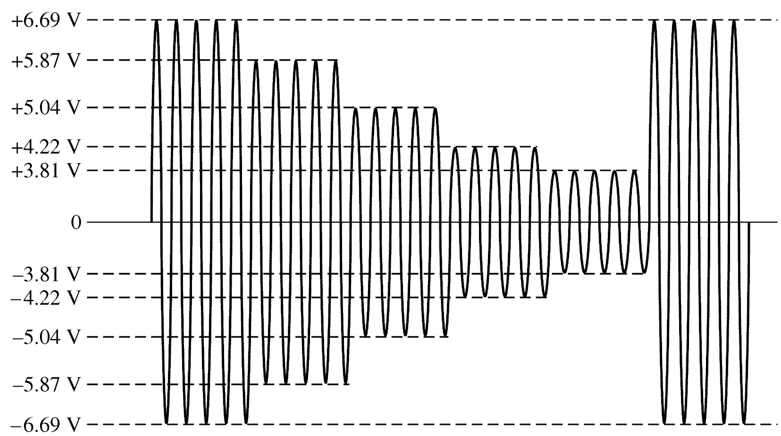


Figure 14-1

20. $$I_{BIAS} = \frac{+9\text{V} - (-9\text{ V}) - 0.7\text{ V}}{39\text{ k}\Omega} = \frac{17.3\text{ V}}{39\text{ k}\Omega} = 444\ \mu\text{A}$$

$V_{TRIG(+)} = I_{BIAS}R_1 = (444\ \mu\text{A})(10\text{ k}\Omega) = \mathbf{+4.44\ V}$

$V_{TRIG(-)} = -I_{BIAS}R_1 = (-444\ \mu\text{A})(10\text{ k}\Omega) = \mathbf{-4.44\ V}$

21. See Figure 14-2.

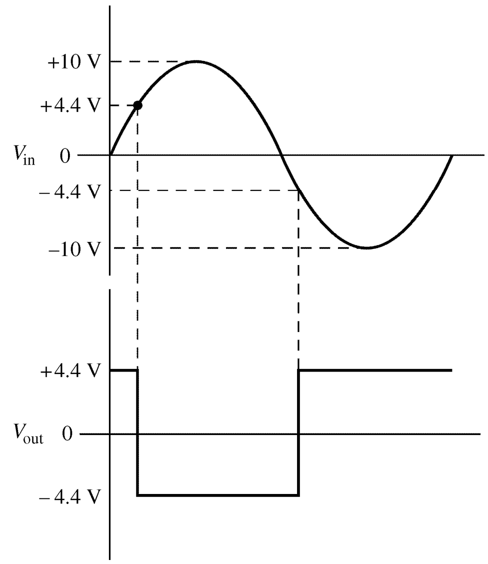


Figure 14-2

Section 14-4 Log and Antilog Amplifiers

22. (a) ln(0.5) = **−0.693**
(b) ln(2) = **0.693**
(c) ln(50) = **3.91**
(d) ln(130) = **4.87**

23. (a) $\log_{10}(0.5)$ = **−0.301**
(b) $\log_{10}(2)$ = **0.301**
(c) $\log_{10}(50)$ = **1.70**
(d) $\log_{10}(130)$ = **2.11**

24. Antilog $x = 10^x$ or e^x, depending on the base used.
INV ln = $e^{1.6}$ = **4.95**
INV log = $10^{1.6}$ = **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. $V_{out} = -R_f I_{EBO}\,\text{antilog}\left(\frac{V_{in}}{25\text{ mV}}\right) = -R_f I_{EBO} e^{\left(\frac{V_{in}}{25\text{ mV}}\right)}$

$V_{out} = -(10\text{ k}\Omega)(60\text{ nA})\,e^{\left(\frac{0.225\text{ V}}{25\text{ mV}}\right)} = -(10\text{ k}\Omega)(60\text{ nA})e^9 = -(10\text{ k}\Omega)(60\text{ nA})(8103) = \mathbf{-4.86\ V}$

29. $V_{out(max)} \cong -(0.025\text{ V})\ln\left(\frac{V_{in}}{I_{EBO}R_{in}}\right) = -(0.025\text{ V})\ln\left(\frac{1\text{ V}}{(60\text{ nA})(47\text{ k}\Omega)}\right)$

$= -(0.025\text{ V})\ln(354.6) = \mathbf{-147\ mV}$

$V_{out(min)} \cong -(0.025\text{ V})\ln\left(\frac{V_{in}}{I_{EBO}R_{in}}\right) = -(0.025\text{ V})\ln\left(\frac{100\text{ mV}}{(60\text{ nA})(47\text{ k}\Omega)}\right)$

$= -(0.025\text{ V})\ln(35.5) = \mathbf{-89.2\ mV}$

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 Op-Amp Circuits

30. (a) $V_{IN} = V_Z = 4.7$ V

$I_L = \frac{V_{IN}}{R_i} = \frac{4.7\text{ V}}{1.0\text{ k}\Omega} = \mathbf{4.7\ mA}$

(b) $V_{IN} = \left(\frac{10\text{ k}\Omega}{20\text{ k}\Omega}\right)12\text{ V} = 6\text{ V}$

$R_i = 10\text{ k}\Omega \,\|\, 10\text{ k}\Omega + 100\ \Omega = 5.1\text{ k}\Omega$

$I_L = \frac{V_{IN}}{R_i} = \frac{6\text{ V}}{5.1\text{ k}\Omega} = \mathbf{1.18\ mA}$

31. See Figure 14-3.

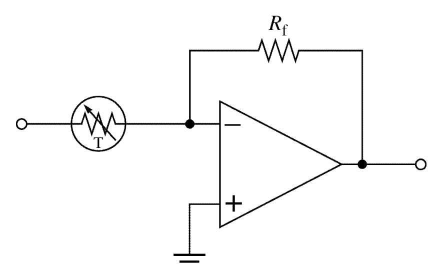


Figure 14-3

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 32 through 36 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).

32. R_G leaky

33. R open

34. R_f open

35. Zener diode open

36. Lower 10 kΩ 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. $BW = f_c$ = **800 Hz**

3. $f_c = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi(2.2\text{ k}\Omega)(0.0015\ \mu\text{F})}$ = **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 kHz − 3.2 kHz = 0.7 kHz = **700 Hz**

$f_0 = \sqrt{f_{c1}f_{c2}} = \sqrt{(3.2\text{ kHz})(3.9\text{ kHz})}$ = 3.53 kHz

$Q = \dfrac{f_0}{BW} = \dfrac{3.53\text{ kHz}}{700\text{ Hz}}$ = **5.04**

6. $Q = \dfrac{f_0}{BW}$

$f_0 = Q(BW)$ = 15(1 kHz) = **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 = **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 = **1.44** **Approximately Butterworth**

(c) 3rd order, 2 stages, 1st stage (2 poles):

$DF = 2 - \dfrac{R_3}{R_4} = 2 - \dfrac{330\ \Omega}{1.0\text{ k}\Omega}$ = **1.67**

2nd stage (1 pole):

$DF = 2 - \dfrac{R_6}{R_7}$ = **1.67** **Not Butterworth**

8. (a) From Table 15-1 in the textbook, the damping factor must be 1.414; therefore,

$$\frac{R_3}{R_4} = 0.586$$

$R_3 = 0.586R_4 = 0.586(1.2\text{ k}\Omega) = \mathbf{703\ \Omega}$
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

$$\frac{R_3}{R_4} = 1$$

$R_3 = R_4 = R_6 = R_7 = \mathbf{1\ k\Omega}$ (for both stages)

9. (a) Chebyshev
(b) Butterworth
(c) Bessel
(d) Butterworth

Section 15-3 Active Low-Pass Filters

10. **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**

11. $$f_c = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}} = \frac{1}{2\pi\sqrt{R_5R_6C_3C_4}} = \frac{1}{2\pi\sqrt{(4.7\text{ k}\Omega)(6.8\text{ k}\Omega)(0.22\ \mu\text{F})(0.1\ \mu\text{F})}} = \mathbf{190\ Hz}$$

12. $R = R_1 = R_2 = R_5 = R_6$ 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 $R = \mathbf{3.9\ k\Omega}$ (for both stages)

13. 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.

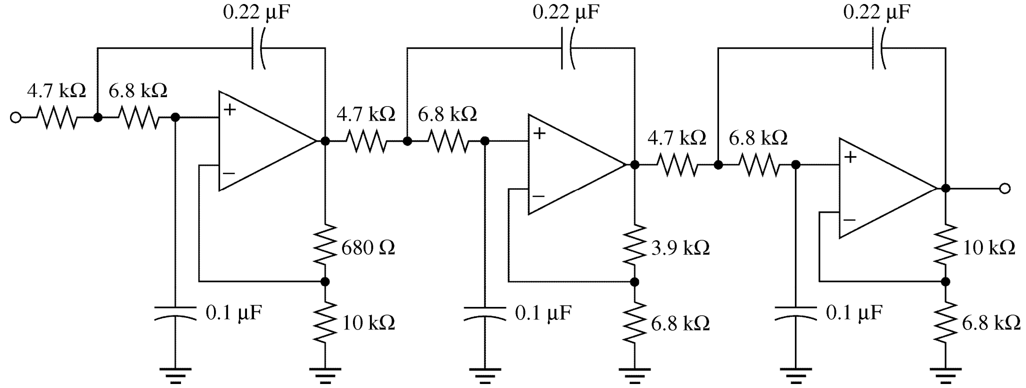


Figure 15-1

14. See Figure 15-2.

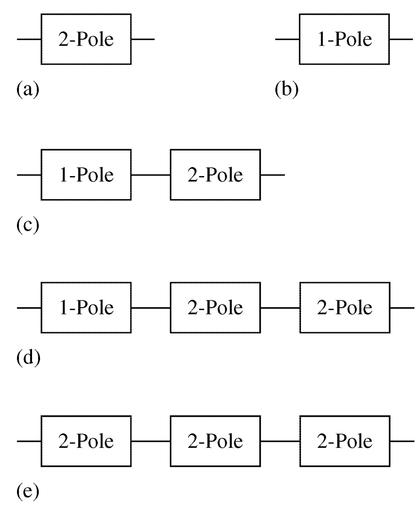


Figure 15-2

Section 15-4 Active High-Pass Filters

15. Exchange the positions of the resistors and the capacitors. See Figure 15-3.

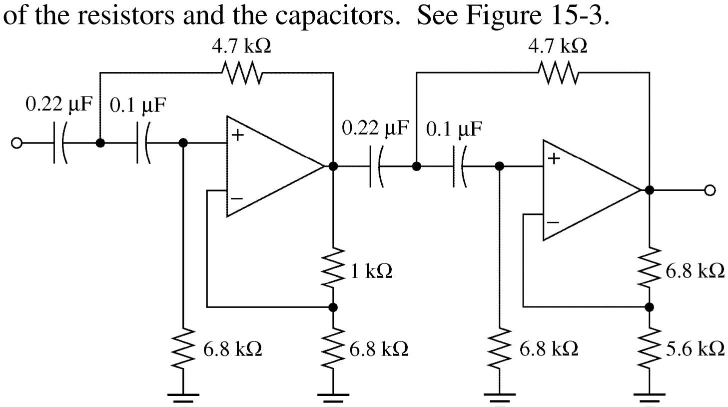


Figure 15-3

16. $f_c = \dfrac{1}{2\pi RC}$

$f_0 = \dfrac{190\text{ Hz}}{2} = 95\text{ Hz}$

$R = \dfrac{1}{2\pi f_c C} = \dfrac{1}{2\pi(95\text{ Hz})(0.22\ \mu\text{F})} = 7615\ \Omega$

Let $R = 7.5$ kΩ. Change R_1, R_2, R_5 and R_6 to **7.5 kΩ**.

17. (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

18. (a) Cascaded high-pass/low-pass filters
(b) Multiple feedback
(c) State variable

19. (a) 1st stage:

$f_{c1} = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi(1.0\text{ k}\Omega)(0.047\ \mu\text{F})} = 3.39\text{ kHz}$

2nd stage:

$f_{c2} = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi(1.0\text{ k}\Omega)(0.022\ \mu\text{F})} = 7.23\text{ kHz}$

$f_0 = \sqrt{f_{c1}f_{c2}} = \sqrt{(3.39\text{ kHz})(7.23\text{ kHz})} = \mathbf{4.95\text{ kHz}}$

$BW = 7.23\text{ kHz} - 3.39\text{ Hz} = \mathbf{3.84\text{ kHz}}$

(b) $f_0 = \dfrac{1}{2\pi C}\sqrt{\dfrac{R_1 + R_3}{R_1R_3R_2}} = \dfrac{1}{2\pi(0.022\ \mu\text{F})}\sqrt{\dfrac{47\text{ k}\Omega + 1.8\text{ k}\Omega}{(47\text{ k}\Omega)(1.8\text{ k}\Omega)(150\text{ k}\Omega)}} = \mathbf{449\text{ Hz}}$

$Q = \pi f_0 CR_2 = \pi(449\text{ Hz})(0.022\ \mu\text{F})(150\text{ k}\Omega) = 4.66$

$BW = \dfrac{f_0}{Q} = \dfrac{449\text{ Hz}}{4.66} = \mathbf{96.4\text{ Hz}}$

(c) For each integrator:

$f_c = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi(10\text{ k}\Omega)(0.001\ \mu\text{F})} = 15.9\text{ kHz}$

$f_0 = f_c = \mathbf{15.9\text{ kHz}}$

$Q = \dfrac{1}{3}\left(\dfrac{R_5}{R_6} + 1\right) = \dfrac{1}{3}\left(\dfrac{560\text{ k}\Omega}{10\text{ k}\Omega} + 1\right) = \dfrac{1}{3}(56 + 1) = 19$

$BW = \dfrac{f_0}{Q} = \dfrac{15.9\text{ kHz}}{19} = \mathbf{838\text{ Hz}}$

20. $Q = \frac{1}{3}\left(\frac{R_5}{R_6} + 1\right)$

Select R_6 = **10 kΩ**.

$Q = \frac{R_5}{3R_6} + \frac{1}{3} = \frac{R_5 + R_6}{3R_6}$

$3R_6Q = R_5 + R_6$

$R_5 = 3R_6Q - R_6$ = 3(10 kΩ)(50) − 10 kΩ = 1500 kΩ − 10 kΩ = **1490 kΩ**

$f_0 = \frac{1}{2\pi(12\text{ k}\Omega)(0.01\,\mu\text{F})}$ = 1.33 kHz

$BW = \frac{f_0}{Q} = \frac{1.33\text{ kHz}}{50}$ = **26.6 Hz**

Section 15-6 Active Band-Stop Filters

21. See Figure 15-4.

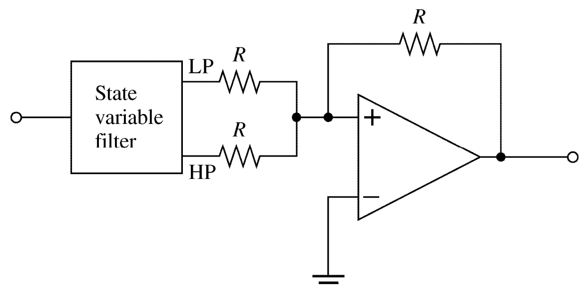


Figure 15-4

22. $f_0 = f_c = \frac{1}{2\pi RC}$

Let C remain 0.01 μF.

$R = \frac{1}{2\pi f_0 C} = \frac{1}{2\pi(120\text{ Hz})(0.01\,\mu\text{F})}$ = **133 kΩ**

Change R in the integrators from 12 kΩ to 133 kΩ.

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 23 through 31 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).

23. R_4 shorted

24. R_3 open

25. C_3 shorted

26. R_5 open

27. R_1 open

28. R_2 shorted

29. R_1 open

30. C_2 open

31. 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.

$A_{cl} = A_v B = 1$

$B = \frac{1}{A_v} = \frac{1}{75}$ = **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. $\frac{V_{out}}{V_{in}} = \frac{1}{3}$

$V_{out} = \left(\frac{1}{3}\right)V_{in} = \frac{2.2\text{ V}}{3}$ = **733 mV**

6. $f_r = \frac{1}{2\pi RC} = \frac{1}{2\pi(6.2\text{ k}\Omega)(0.02\ \mu\text{F})}$ = **1.28 kHz**

7. $R_1 = 2R_2$

$R_2 = \frac{R_1}{2} = \frac{100\text{ k}\Omega}{2}$ = **50 kΩ**

8. When dc power is first applied, both zener diodes appear as opens because there is insufficient output voltage. This places R_3 in series with R_1, thus increasing the closed-loop gain to a value greater than unity to assure that oscillation will begin.

9. $R_f = (A_v - 1)(R_3 + r'_{ds}) = (3 - 1)(820\ \Omega + 350\ \Omega)$ = **2.34 kΩ**

10. $f_r = \dfrac{1}{2\pi(1.0\ \text{k}\Omega)(0.015\ \mu\text{F})} = \mathbf{10.6\ kHz}$

11. $B = \dfrac{1}{29}$

$A_{cl} = \dfrac{1}{B} = 29$

$A_{cl} = \dfrac{R_f}{R_i}$

$R_f = A_{cl}R_i = 29(4.7\ \text{k}\Omega) = \mathbf{136\ k\Omega}$

$f_r = \dfrac{1}{2\pi\sqrt{6}(4.7\ \text{k}\Omega)(0.022\ \mu\text{F})} = \mathbf{628\ Hz}$

Section 16-4 Oscillators with LC Feedback Circuits

12. (a) *Colpitts*: C_1 and C_3 are the feedback capacitors.

$f_r = \dfrac{1}{2\pi\sqrt{L_1 C_T}}$

$C_T = \dfrac{C_1 C_3}{C_1 + C_3} = \dfrac{(100\ \mu\text{F})(1000\ \text{pF})}{1100\ \text{pF}} = 90.9\ \text{pF}$

$f_r = \dfrac{1}{2\pi\sqrt{(5\ \text{mH})(90.9\ \text{pF})}} = \mathbf{236\ kHz}$

(b) *Hartley*:

$f_r = \dfrac{1}{2\pi\sqrt{L_T C_2}}$

$L_T = L_1 + L_2 = 1.5\ \text{mH} + 10\ \text{mH} = 11.5\ \text{mH}$

$f_r = \dfrac{1}{2\pi\sqrt{(11.5\ \text{mH})(470\ \text{pF})}} = \mathbf{68.5\ kHz}$

13. $B = \dfrac{47\ \text{pF}}{470\ \text{pF}} = 0.1$

The condition for sustained oscillation is

$A_v = \dfrac{1}{B} = \dfrac{1}{0.1} = \mathbf{10}$

Section 16-5 Relaxation Oscillators

14. Triangular waveform.

$f = \dfrac{1}{4R_1C}\left(\dfrac{R_2}{R_3}\right) = \dfrac{1}{4(22\ \text{k}\Omega)(0.022\ \mu\text{F})}\left(\dfrac{56\ \text{k}\Omega}{18\ \text{k}\Omega}\right) = \mathbf{1.61\ kHz}$

Chapter 16

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. $$T = \frac{V_p - V_F}{\left(\frac{|V_{IN}|}{RC}\right)}$$

$$V_p = \left(\frac{R_5}{R_4 + R_5}\right)12\text{ V} = \left(\frac{47\text{ k}\Omega}{147\text{ k}\Omega}\right)12\text{ V} = 3.84\text{ V}$$

PUT triggers at about +3.84 V (ignoring the 0.7 V drop)
Amplitude = +3.84 V − 1 V = **2.84 V**

$$V_{IN} = \left(\frac{R_2}{R_1 + R_2}\right)(-12\text{ V}) = \left(\frac{22\text{ k}\Omega}{122\text{ k}\Omega}\right)(-12\text{ V}) = -2.16\text{ V}$$

$$T = \frac{3.84\text{ V} - 1\text{ V}}{\left(\frac{2.16\text{ V}}{(100\text{ k}\Omega)(0.0022\ \mu\text{F})}\right)} = 289\ \mu\text{s}$$

$$f = \frac{1}{T} = \frac{1}{289\ \mu\text{s}} = \mathbf{3.46\ kHz}$$

See Figure 16-1.

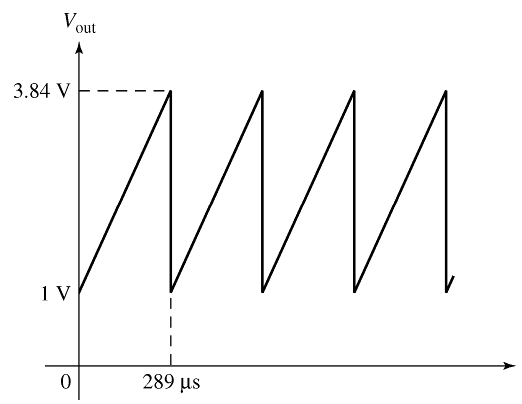


Figure 16-1

17. $V_G = 5$ V. Assume $V_{AK} = 1$ V.
$R_5 = 47$ kΩ

$$V_G = \left(\frac{R_5}{R_4 + R_5}\right)12\text{ V}$$

Change R_4 to get $V_G = 5$ V.
$5\text{ V}(R_4 + 47\text{ k}\Omega) = (47\text{ k}\Omega)12\text{ V}$
$R_4(5\text{ V}) = (47\text{ k}\Omega)12\text{ V} - (47\text{ k}\Omega)5\text{ V}$

$$R_4 = \frac{(12\text{ V} - 5\text{ V})47\text{ k}\Omega}{5\text{ V}} = \mathbf{65.8\text{ k}\Omega}$$

18.
$$T = \frac{V_p - V_F}{\left(\frac{V_{IN}}{RC}\right)}$$

$$V_p = \left(\frac{V_{IN}}{RC}\right)T + V_F = \left(\frac{3\text{ V}}{(4.7\text{ k}\Omega)(0.001\ \mu\text{F})}\right)10\ \mu\text{s} + 1\text{ V} = 7.38\text{ V}$$

$V_{pp(out)} = V_p - V_F = 7.38\text{ V} - 1\text{ V} = \mathbf{6.38\text{ V}}$

Section 16-6 The 555 Timer as an Oscillator

19.
$$\frac{1}{3}V_{CC} = \frac{1}{3}(10\text{ V}) = \mathbf{3.33\text{ V}}$$

$$\frac{2}{3}V_{CC} = \frac{2}{3}(10\text{ V}) = \mathbf{6.67\text{ V}}$$

20.
$$f = \frac{1.44}{(R_1 + 2R_2)C_{ext}} = \frac{1.44}{(1.0\text{ k}\Omega + 6.6\text{ k}\Omega)(0.047\ \mu\text{F})} = \mathbf{4.03\text{ kHz}}$$

21.
$$f = \frac{1.44}{(R_1 + 2R_2)C_{ext}}$$

$$C_{ext} = \frac{1.44}{(R_1 + 2R_2)f} = \frac{1.44}{(1.0\text{ k}\Omega + 6.6\text{ k}\Omega)(25\text{ kHz})} = \mathbf{0.0076\ \mu F}$$

22.
$$\text{Duty cycle (dc)} = \frac{R_1 + R_2}{R_1 + 2R_2} \times 100\%$$

$dc(R_1 + 2R_2) = (R_1 + R_2)100$
$75(3.3\text{ k}\Omega + 2R_2) = (3.3\text{ k}\Omega + R_2)100$
$75(3.3\text{ k}\Omega) + 150R_2 = 100(3.3\text{ k}\Omega) + 100R_2$
$150R_2 - 100R_2 = 100(3.3\text{ k}\Omega) - 75(3.3\text{ k}\Omega)$
$50R_2 = 25(3.3\text{ k}\Omega)$

$$R_2 = \frac{25(3.3\text{ k}\Omega)}{50} = \mathbf{1.65\text{ k}\Omega}$$

Chapter 16

Multisim Troubleshooting Problems

The solutions showing instrument connections for Problems 23 through 28 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).

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 = $\left(\dfrac{\Delta V_{\text{OUT}}}{\Delta V_{\text{IN}}}\right)100\% = \left(\dfrac{2\text{ mV}}{6\text{ V}}\right)100\% = \mathbf{0.0333\%}$

2. Percent line regulation = $\left(\dfrac{\Delta V_{\text{OUT}}/V_{\text{OUT}}}{\Delta V_{\text{IN}}}\right)100\% = \left(\dfrac{2\text{ mV}/8\text{ V}}{6\text{ V}}\right)100\% = \mathbf{0.00417\%/V}$

3. Percent load regulation = $\left(\dfrac{V_{\text{NL}}/V_{\text{FL}}}{\Delta V_{\text{FL}}}\right)100\% = \left(\dfrac{10\text{ V} - 9.90\text{ V}}{9.90\text{ V}}\right)100\% = \mathbf{1.01\%}$

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.

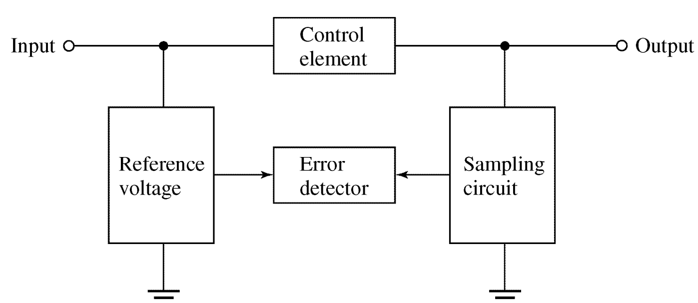


Figure 17-1

6. $V_{\text{OUT}} = \left(1 + \dfrac{R_2}{R_3}\right)V_{\text{REF}} = \left(1 + \dfrac{33\text{ k}\Omega}{10\text{ k}\Omega}\right)2.4\text{ V} = \mathbf{10.3\text{ V}}$

7. $V_{\text{OUT}} = \left(1 + \dfrac{R_2}{R_3}\right)V_{\text{REF}} = \left(1 + \dfrac{5.6\text{ k}\Omega}{2.2\text{ k}\Omega}\right)2.4\text{ V} = \mathbf{8.51\text{ V}}$

8. For R_3 = 2.2 kΩ:

$$V_{OUT} = \left(1+\frac{R_2}{R_3}\right)V_{REF} = \left(1+\frac{5.6\text{ k}\Omega}{2.2\text{ k}\Omega}\right)2.4\text{ V} = 8.5\text{ V}$$

For R_3 = 4.7 kΩ:

$$V_{OUT} = \left(1+\frac{R_2}{R_3}\right)V_{REF} = \left(1+\frac{5.6\text{ k}\Omega}{4.7\text{ k}\Omega}\right)2.4\text{ V} = 5.26\text{ V}$$

The output voltage **decreases by 3.24 V** when R_3 is changed from 2.2 kΩ to 4.7 kΩ.

9. $$V_{OUT} = \left(1+\frac{R_2}{R_3}\right)V_{REF} = \left(1+\frac{5.6\text{ k}\Omega}{2.2\text{ k}\Omega}\right)2.7\text{ V} = \mathbf{9.57\text{ V}}$$

10. $$I_{L(max)} = \frac{0.7\text{ V}}{R_4}$$

$$R_4 = \frac{0.7\text{ V}}{I_{L(max)}} = \frac{0.7\text{ mA}}{250\text{ mA}} = \mathbf{2.8\ \Omega}$$

$$P = I^2_{L(max)}R_4 = (250\text{ mA})^2 2.8\ \Omega = \mathbf{0.175\text{ W}},\ \text{Use a 0.25 W.}$$

11. $$R_4 = \frac{2.8\ \Omega}{2} = 1.4\ \Omega$$

$$I_{L(max)} = \frac{0.7\text{ V}}{R_4} = \frac{0.7\text{ V}}{1.4\ \Omega} = \mathbf{500\text{ mA}}$$

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. $$\Delta I_C = \frac{\Delta V_{R1}}{R_1} = \frac{1\text{ V}}{100\ \Omega} = \mathbf{10\text{ mA}}$$

14. $$V_{OUT} = \left(1+\frac{R_3}{R_4}\right)V_{REF} = \left(1+\frac{10\text{ k}\Omega}{3.9\text{ k}\Omega}\right)5.1\text{ V} = \mathbf{18.2\text{ V}}$$

$$I_{L1} = \frac{V_{OUT}}{R_{L1}} = \frac{18.2\text{ V}}{1\text{ k}\Omega} = 18.2\text{ mA}$$

$$I_{L2} = \frac{V_{OUT}}{R_{L2}} = \frac{18.2\text{ V}}{1.2\text{ k}\Omega} = 15.2\text{ mA}$$

ΔI_L = 15.2 mA − 18.2 mA = −3.0 mA

$\Delta I_S = -\Delta I_L$ = **3.0 mA**

15. $I_{L(max)} = \frac{V_{IN}}{R_1} = \frac{25\text{ V}}{100\ \Omega}$ = **250 mA**

$P_{R1} = I^2_{L(max)}R_1$ = (250 mA)^{2}100 Ω = **6.25 W**

Section 17-4 Basic Switching Regulators

16. $V_{OUT} = \left(\frac{t_{on}}{T}\right)V_{IN}$

$t_{on} = T - t_{off}$

$T = \frac{1}{f} = \frac{1}{10\text{ kHz}}$ = 0.0001 s = 100 μs

$V_{OUT} = \left(\frac{40\ \mu\text{s}}{100\ \mu\text{s}}\right)12\text{ V}$ = **4.8 V**

17. f = 100 Hz, t_{off} = 6 ms

$T = \frac{1}{f} = \frac{1}{100\text{ Hz}}$ = 10 ms

$t_{on} = T - t_{off}$ = 10 ms − 6 ms = 4 ms

duty cycle = $\frac{t_{on}}{T} = \frac{4\text{ ms}}{10\text{ ms}}$ = 0.4

percent duty cycle = 0.4 × 100% = **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) 7905.2: **−5.2 V**
(c) 7818: **+18 V**
(d) 7924: **−24 V**

21. $V_{OUT} = \left(1 + \frac{R_2}{R_1}\right)V_{REF} + I_{ADJ}R_2 = \left(1 + \frac{10\text{ k}\Omega}{1.0\text{ k}\Omega}\right)1.25\text{ V}$ + (50 μA)(10 kΩ)

= 13.7 V + 0.5 V = **14.3 V**

22. $V_{OUT(min)} = -\left[\left(1+\dfrac{R_{2(min)}}{R_1}\right)V_{REF} + I_{ADJ}R_{2(min)}\right]$

$R_{2(min)} = 0\ \Omega$

$V_{OUT(min)} = -\left(1.25\text{ V}(1+0)+0\right) = \mathbf{-1.25\ V}$

$V_{OUT(max)} = -\left[\left(1+\dfrac{R_{2(max)}}{R_1}\right)V_{REF} + I_{ADJ}R_{2(max)}\right] = -\left[1.25\text{ V}\left(1+\dfrac{10\text{ k}\Omega}{470\ \Omega}\right) + (50\ \mu\text{A})(10\text{ k}\Omega)\right]$

$= -\left(1.25\text{ V}(22.28)+0.5\text{ V}\right) = \mathbf{-28.4\ V}$

23. The regulator current equals the current through $R_1 + R_2$.

$I_{REG} \cong \dfrac{V_{OUT}}{R_1+R_2} = \dfrac{14.3\text{ V}}{11\text{ k}\Omega} = \mathbf{1.3\ mA}$

24. $V_{IN} = 18$ V, $V_{OUT} = 12$ V

$I_{REG(max)} = 2$ mA, $V_{REF} = 1.25$ V

$R_1 = \dfrac{V_{REF}}{I_{REG}} = \dfrac{1.25\text{ V}}{2\text{ mA}} = \mathbf{625\ \Omega}$

Neglecting I_{ADJ}:

$V_{R2} = 12\text{ V} - 1.25\text{ V} = 10.8\text{ V}$

$R_2 = \dfrac{V_{R2}}{I_{REG}} = \dfrac{10.8\text{ V}}{2\text{ mA}} = \mathbf{5.4\ k\Omega}$

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 Applications of IC Voltage Regulators

25. $V_{Rext(min)} = 0.7$ V

$R_{ext} = \dfrac{0.7\text{ V}}{I_{max}} = \dfrac{0.7\text{ V}}{250\text{ mA}} = \mathbf{2.8\ \Omega}$

26. $V_{OUT} = +12$ V

$I_L = \dfrac{12\text{ V}}{10\ \Omega} = 1200\text{ mA} = 1.2\text{ A}$

$I_{ext} = I_L - I_{max} = 1.2\text{ A} - 0.5\text{ A} = 0.7\text{ A}$

$P_{ext} = I_{ext}(V_{IN} - V_{OUT}) = 0.7\text{ A}(15\text{ V} - 12\text{ V}) = 0.7\text{ A}(3\text{ V}) = \mathbf{2.1\ W}$

27. $V_{Rlim(min)} = 0.7$ V

$R_{lim(min)} = \dfrac{0.7\text{ V}}{I_{ext}} = \dfrac{0.7\text{ V}}{2\text{ A}} = \mathbf{0.35\ \Omega}$

See Figure 17-2.

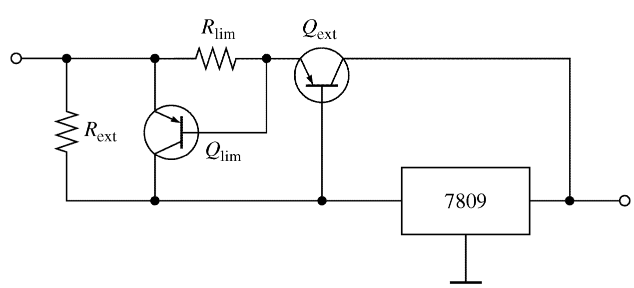


Figure 17-2

28. $R = \dfrac{1.25\text{ V}}{500\text{ mA}} = \mathbf{2.5\ \Omega}$

See Figure 17-3.

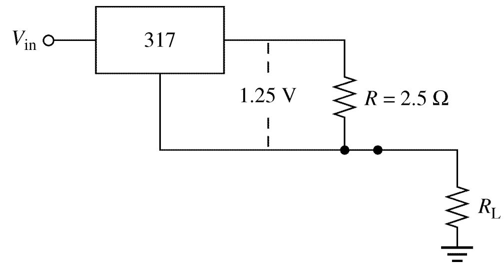


Figure 17-3

29. $I = 500\text{ mA}$

$R = \dfrac{8\text{ V}}{500\text{ mA}} = \mathbf{16\ \Omega}$

See Figure 17-4.

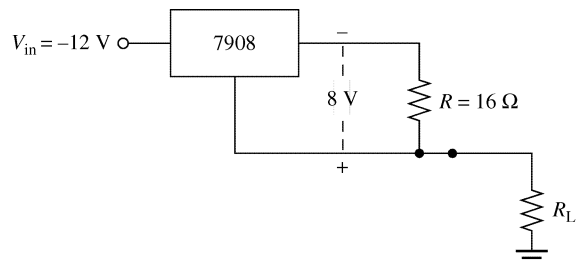


Figure 17-4

30. Connect pin 7 to pin 6.

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
Basic Programming Concepts for Automated Testing

Section 18-1 Programming Basics

1. The five basic instruction types are simple instructions, conditional instructions, loop instructions, branching instructions, and exception instructions.

2. The flowchart symbols are (1) subroutine, (2) decision, (3) continuation, (4) begin/end, (5) input/output, and (6) task.

3. One possible pseudocode description is

```
program PrintAverage
   begin
      input first number
      input second number
      input third number
      sum is first number plus second number plus third number
      average is sum divided by 3
      print average
   end PrintAverage
```

Section 18-2 Automated Testing Basics

4. The automated test system components are (1) test controller, (2) test equipment and instrumentation, (3) test fixture, (4) switching control, (5) switching circuitry, and (6) unit under test (UUT).

5. Advantages of electromechanical relays are good electrical isolation and high current and voltage handling ability.

Section 18-3 The Simple Sequential Program

6. The process flow for a simple sequential program is linear in which the program begins, executes a series of instructions in sequence, and then terminates.

7. The flowchart represents a simple sequential program, as none of the program operations alters the sequence of program execution from its linear process flow.

Section 18-4 Conditional Execution

8. Because the start value is 7 and not less than 5, the top-level IF statement is skipped. The program enters the top-level ELSE, sets the output value to the 7 – 2 = 5 and tests whether the start value is greater than 7. The start value of 7 is not greater than 7, so the nested top-level IF statement is skipped. The program enters the top-level nested ELSE statement and tests whether the start value is greater than 6 . The start value of 7 is greater than 6, so the output value is set to 5 / 3 = 1.6. The program exits the nested IF-THEN-ELSE instruction and prints 1.6 as the output value.

9. One possible pseucode description is

```
NewIdentifyKeyValue
   begin
      input key value
      case (key value)
         begin case
            "1":     print "Key value equals 1"
                     break
            "2":     print "Key value equals 2"
                     break
            "3":     print "Key value equals 3"
                     break
            default: print "Key value is more than 3"
                     break
         end case
   end NewIdentifyKeyValue
```

Section 18-5 Program Loops

10. Loop 1 corresponds to a WHILE-DO loop, Loop 2 corresponds to a FOR-TO-STEP loop, and Loop 3 corresponds to a REPEAT-UNTIL loop.

11. The index value starts at 1 and the step value increases the index value by 2 for each loop, so the FOR-TO-STEP loop will execute once for each odd index value from 1 through 9 and exit on an index value of 11. The sum begins at 0 and each loop will add the index value plus 1, so

$$\begin{aligned} \text{sum} &= (1+1) + (3+1) + (5+1) + (7+1) + (9+1) \\ &= 2 + 4 + 6 + 8 + 10 \\ &= 30 \end{aligned}$$

12. The outer loop will execute three times and the inner loop will execute a number of times equal to the index1, the outer loop index value. The sum begins at 0 and each loop will add 1 to the sum, so

Index1 equals 1: Index1 does not exceed end value of 3, so program enters inner loop.
Inner loop executes 1 time, so sum = 0 + 1 = 1.

	Index1 adjusted by step value of 1 to 1 + 1 = 2.
Index1 equals 2:	Index1 does not exceed end value of 3, so program enters inner loop. Inner loop executes 2 times, so sum = 1 + 1 + 1 = 3. Index1 adjusted by step value of 1 to 2 + 1 = 3.
Index1 equals 3:	Index1 does not exceed end value of 3, so program enters inner loop. Inner loop executes 3 times, so sum = 3 + 1 + 1 + 1 = 6. Index1 adjusted by step value of 1 to 3 + 1 = 4.
Index1 equals 4:	Index1 exceeds end value of 3, so program skips outer loop and prints the sum value of 6.

Section 18-6 Branches and Subroutines

13. One reason that programs should avoid using unconditional branches is that unconditional branches too often encourage poor programming practices by compensating for poorly designed code. A second reason is that unrestricted unconditional branching typically results in "spaghetti code" that is difficult to modify and maintain. A third reason is that replacing the branch instruction with the desired target instruction(s) produces the same result as the unconditional branch, so that unconditional branches are often unnecessary.

14. One possible pseudocode description is

```
procedure CompareValues(FirstResistor, SecondResistor)
   begin
      input FirstResistor value
      input SecondResistor value
      print "First resistor value is " and FirstResistor value
      print "Second resistor value is " and SecondResistor value
      if (FirstResistor value is greater than SecondResistor
            value) then
         begin if
            print "First resistor value is greater than second
                  resistor value"
         end if
      else
         begin else
            print "Second resistor value is greater than first
                  resistor value"
         end else
   end CompareValues
```

Chapter 19 (Website) Electronic Communications Systems and Devices

Section 19-1 Basic Receivers

1. See Figure 19-1.

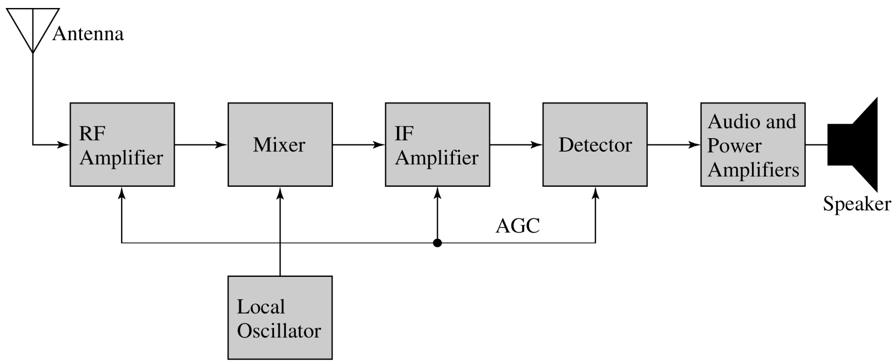


Figure 19-1

2. See Figure 19-2.

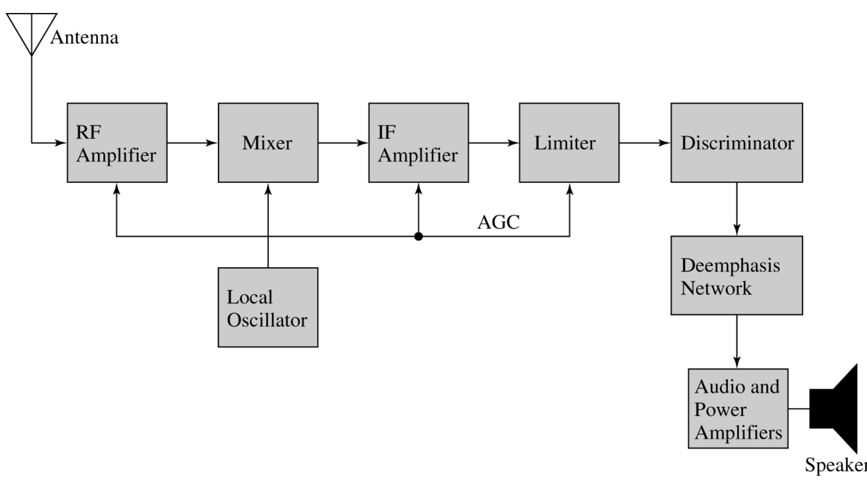


Figure 19-2

3. f_{LO} = 680 kHz + 455 kHz = **1135 kHz**

4. f_{LO} = 97.2 MHz + 10.7 MHz = **107.9 MHz**

5. f_{RF} = 101.9 MHz − 10.7 MHz = **91.2 MHz**
f_{IF} = **10.7 MHz** (always)

Chapter 19

Section 19-2 The Linear Multiplier

6. (a) $V_{out} \cong$ **−2.5 V**
(b) $V_{out} \cong$ **−1.6 V**
(c) $V_{out} \cong$ **+1.0 V**
(d) $V_{out} \cong$ **+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 19-3 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. $f_1 = \dfrac{9\text{ cycles}}{1\text{ ms}} = 9000\text{ cycles/s} = 9\text{ kHz}$
$f_2 = \dfrac{1\text{ cycle}}{1\text{ ms}} = 1000\text{ cycles/s} = 1\text{ kHz}$
$f_{diff} = f_1 - f_2 = 9\text{ kHz} - 1\text{ kHz} = \mathbf{8\ kHz}$
$f_{sum} = f_1 + f_2 = 9\text{ kHz} + 1\text{ kHz} = \mathbf{10\ kHz}$

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. $f_1 = \dfrac{18\text{ cycles}}{10\ \mu\text{s}} = 1.8\text{ MHz}$
$f_2 = \dfrac{1\text{ cycle}}{10\ \mu\text{s}} = 100\text{ kHz}$
$f_{diff} = f_1 - f_2 = 1.8\text{ MHz} - 100\text{ kHz} = \mathbf{1.7\ MHz}$
$f_{sum} = f_1 + f_2 = 1.8\text{ MHz} + 100\text{ kHz} = \mathbf{1.9\ MHz}$
$f_c = \mathbf{1.8\ MHz}$

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. $f_c = \dfrac{f_{diff} + f_{sum}}{2} = \dfrac{8.47\text{ kHz} + 853\text{ KHz}}{2}$ = **850 kHz**

$f_m = f_c - f_{diff}$ = 850 kHz − 847 kHz = **3 kHz**

16. $f_{diff(min)}$ = 600 kHz − 3 kHz = **597 kHz**
$f_{diff(max)}$ = 600 kHz − 300 Hz = **599.7 kHz**
$f_{sum(min)}$ = 600 kHz + 300 kHz = **600.3 kHz**
$f_{sum(max)}$ = 600 kHz + 3 kHz = **603 kHz**
See Figure 19-3.

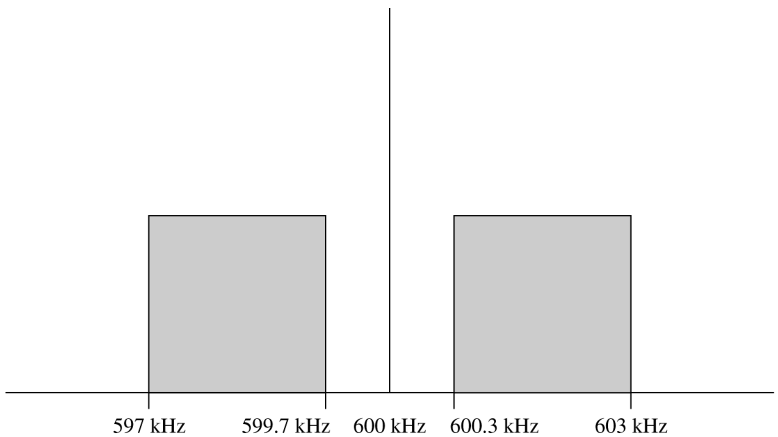


Figure 19-3

Section 19-4 The Mixer

17. $(\sin A)(\sin B) = \dfrac{1}{2}[\cos(A - B) - \cos(A + B)]$

$V_{in(1)} = 0.2\text{ V} \sin[2\pi(2200\text{ kHz})t]$
$V_{in(2)} = 0.15\text{ V} \sin[2\pi(3300\text{ kHz})t]$
$V_{in(1)}V_{in(2)} = (0.2\text{ V})(0.15\text{ V}) \sin[2\pi(2200\text{ kHz})t] \sin[2\pi(3300\text{ kHz})t]$
$V_{out} = \dfrac{(0.2\text{ V})(0.15\text{ V})}{2}[\cos 2\pi(3300\text{ kHz} - 2200\text{ kHz})t - \cos 2\pi(3300\text{ kHz} + 2200\text{ kHz})t]$
$V_{out} = 15\text{ mV} \cos[2\pi(1100\text{ kHz})t] - 15\text{ mV} \cos[2\pi(5500\text{ kHz})t]$

18. $f_{IF} = f_{LO} - f_c$ = 986.4 kHz − 980 kHz = **6.4 kHz**

Chapter 19

Section 19-5 AM Demodulation

19. See Figure 19-4.

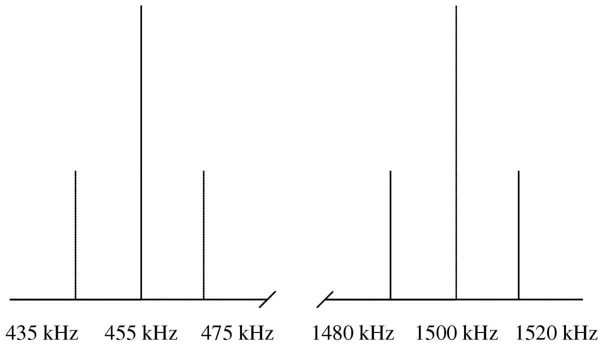


Figure 19-4

20. See Figure 19-5.

21. See Figure 19-6.

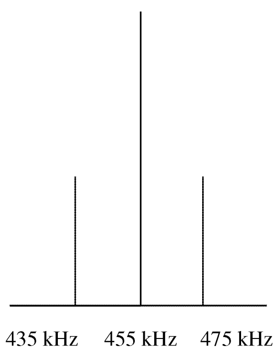


Figure 19-5

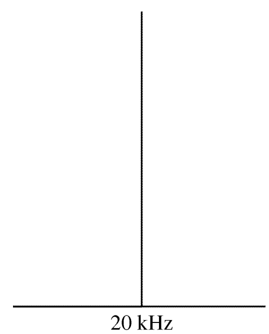


Figure 19-6

Section 19-6 IF and Audio Amplifiers

22. $f_c - f_m$ = 1.2 MHz − 8.5 kHz = 1.1915 MHz
$f_c + f_m$ = 1.2 MHz + 8.5 kHz = 1.2085 MHz
f_c = 1.2 MHz
$f_{\text{LO}} - f_m$ = 455 kHz − 8.5 kHz = 446.5 kHz
$f_{\text{LO}} + f_m$ = 455 kHz + 8.5 kHz = 463.5 kHz
f_{LO} = 455 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.

24. C_4 between pins 1 and 8 makes the gain 200.
With R_1 set for minimum input, $V_{in} = 0$ V.
$V_{out(min)} = A_v V_{in(min)} = 200(0\text{ V}) = \mathbf{0\ V}$
With R_1 set for maximum input, $V_{in} = 10$ mV rms.
$V_{out(max)} = A_v V_{in(max)} = 200(10\text{ mV}) = \mathbf{2\ V\ rms}$

Section 19-7 Frequency Modulation

25. The modulating input signal is applied to the control voltage terminal of the VCO. As the input signal amplitude varies, the output frequency of the VCO varies proportionately.

26. An FM signal differs from an AM signal in that the information is contained in frequency variations of the carrier rather than amplitude variations.

27. Varactor

Section 19-8 The Phase-Locked Loop (PLL)

28. See Figure 19-7.

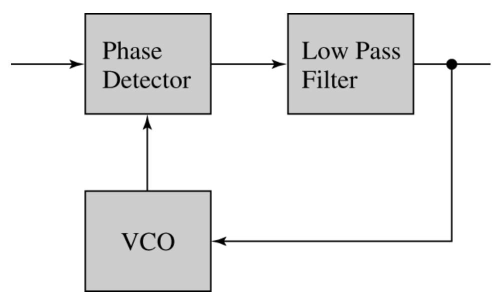


Figure 19-7

29. (a) The VCO signal is locked onto the incoming signal and therefore its frequency is equal to the incoming frequency of **10 MHz**.

(b) $V_c = \dfrac{V_i V_o}{2}\cos\theta_e \; \dfrac{(250\text{ mV})(400\text{ mV})}{2}\cos(30° - 15°) = (0.050)(0.966) = \mathbf{48.3\ mV}$

30. $\Delta f_o = +3.6$ kHz, $\Delta V_c = +0.5$ V

$$K = \frac{\Delta f_o}{\Delta V_c} = \frac{+3.6\text{ kHz}}{+0.5\text{ V}} = \mathbf{7.2\ kHz/V}$$

31. $K = 1.5$ kHz/V, $\Delta V_c = +0.67$ V

$$K = \frac{\Delta f_o}{\Delta V_c}$$

$\Delta f_o = K\Delta V_c = (1.5\text{ kHz/V})(+0.67\text{ V}) = \mathbf{1005\ Hz}$

32. For a PLL to acquire lock the following conditions are needed:

(1) The difference frequency, $f_0 - f_i$ must fall within the filter's bandwidth.

(2) The maximum frequency deviation of the VCO frequency, Δf_{max}, must be sufficient to permit f_0 to change to equal f_i.

33. The free-running frequency:

$$f_o = \frac{1.2}{4R_1C_1} = \frac{1.2}{4(3.9\,\text{k}\Omega)(330\,\text{pF})} = \mathbf{233\ kHz}$$

The lock range:

$$f_{lock} = \pm\frac{8f_o}{V_{CC}} = \pm\frac{8(233\,\text{kHz})}{18\,\text{V}} = \pm\frac{1.864\,\text{MHz}}{18\,\text{V}} = \mathbf{\pm 104\ kHz}$$

The capture range:

$$f_{cap} = \pm\frac{1}{2\pi}\sqrt{\left(\frac{2\pi f_{lock}}{3600\times C_2}\right)}$$

$$= \pm\frac{1}{2\pi}\sqrt{\left(\frac{2\pi(103.6\,\text{kHz})}{3600\times 0.22\,\mu\text{F}}\right)} = \pm\frac{1}{2\pi}\sqrt{\left(\frac{650.9\,\text{kHz}}{792\,\mu\text{F}}\right)} = \mathbf{\pm 4.56\ kHz}$$

Section 19-9 Fiber Optics

34. The light ray will be **reflected** because the angle of incidence (30°) is greater than the critical angle (15°).

35. $\theta_C = \cos^{-1}(n_2/n_1) = \cos^{-1}(1.25/1.55) = \mathbf{36.2°}$