chapter 12

Power Amplifiers

In a stereo, radio, or television, the input signal is small. After several stages of voltage gain, however, the signal becomes large and uses the entire load line. In these later stages of a system, the collector currents are much larger because the load impedances are much smaller. Stereo amplifier speakers, for example, may have an impedance of 8 Ω or less.

As indicated in Chap. 6, small-signal transistors have a power rating of less than 1 W, whereas power transistors have a power rating of more than 1 W. Small-signal transistors are typically used at the front end of systems where the signal power is low, and power transistors are used near the end of systems because the signal power and current are high.

Objectives

After studying this chapter, you should be able to:

- Show how the dc load line, ac load line, and *Q* point are determined for CE and CC power amplifiers.
- Calculate the maximum peak-to-peak (MPP) unclipped ac voltage that is possible with CE and CC power amplifiers.
- Describe the characteristics of amplifiers, including classes of operation, types of coupling, and frequency ranges.
- Draw a schematic of class B/AB push-pull amplifier and explain its operation.
- Determine the efficiency of transistor power amplifiers.
- Discuss the factors that limit the power rating of a transistor and what can be done to improve the power rating.

Chapter Outline

Vocabulary

ac compliance
ac load line
audio amplifier
bandwidth (BW)
capacitive coupling
class A operation
class AB operation
class B operation
class C operation
compensating diodes
crossover distortion
current drain
direct coupling
driver stage
duty cycle
efficiency
harmonics
large-signal operation
narrowband amplifier
power amplifier
power gain
preamp
push-pull circuit
radio-frequency (RF) amplifier
thermal runaway
transformer coupling
tuned RF amplifier
wideband amplifier

GOOD TO KNOW

As we progress through the letters A, B, and C designating the various classes of operation, we can see that linear operation occurs for shorter and shorter intervals of time. A class D amplifier is one whose output is switched on and off; that is, it essentially spends zero time during each input cycle in the linear region of operation. A class D amplifier is often used as a pulse-width modulator, which is a circuit whose output pulses have widths that are proportional to the amplitude level of the amplifier's input signal.

GOOD TO KNOW

Most integrated circuit amplifiers use direct coupling between stages.

12-1 Amplifier Terms

There are different ways to describe amplifiers. For instance, we can describe them by their class of operation, by their interstage coupling, or by their frequency range.

Classes of Operation

Class A operation of an amplifier means that the transistor operates in the active region at all times. This implies that collector current flows for 360° of the ac cycle, as shown in Fig. 12-1*a*. With a class A amplifier, the designer usually tries to locate the *Q* point somewhere near the middle of the load line. This way, the signal can swing over the maximum possible range without saturating or cutting off the transistor, which would distort the signal.

Class B operation is different. It means that collector current flows for only half the cycle (180°), as shown in Fig. 12-1*b*. To have this kind of operation, a designer locates the *Q* point at cutoff. Then, only the positive half of ac base voltage can produce collector current. This reduces the wasted heat in power transistors.

Class C operation means that collector current flows for less than 180° of the ac cycle, as shown in Fig. 12-1*c*. With class C operation, only part of the positive half cycle of ac base voltage produces collector current. As a result, we get brief pulses of collector current like those of Fig. 12-1*c*.

Types of Coupling

Figure 12-2*a* shows **capacitive coupling.** The coupling capacitor transmits the amplified ac voltage to the next stage. Figure 12-2*b* illustrates **transformer coupling.** Here the ac voltage is coupled through a transformer to the next stage. Capacitive coupling and transformer coupling are both examples of ac coupling, which blocks the dc voltage.

Direct coupling is different. In Fig. 12-2*c*, there is a direct connection between the collector of the first transistor and the base of the second transistor.

Figure 12-1 Collector current: (*a*) class A; (*b*) class B; (*c*) class C.

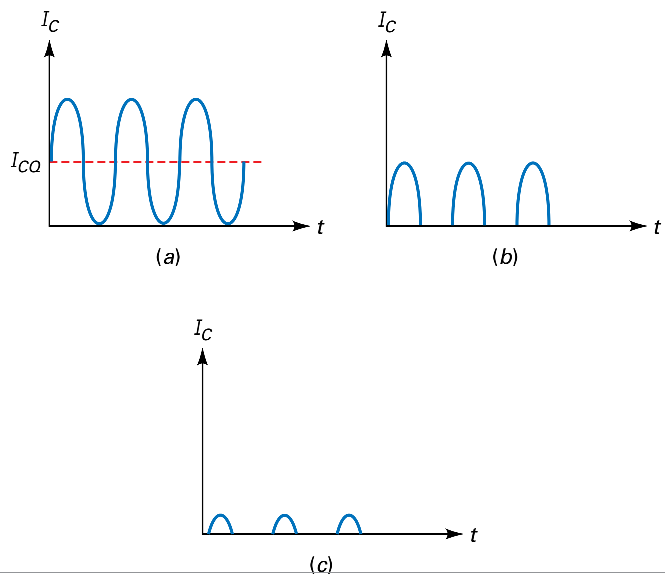
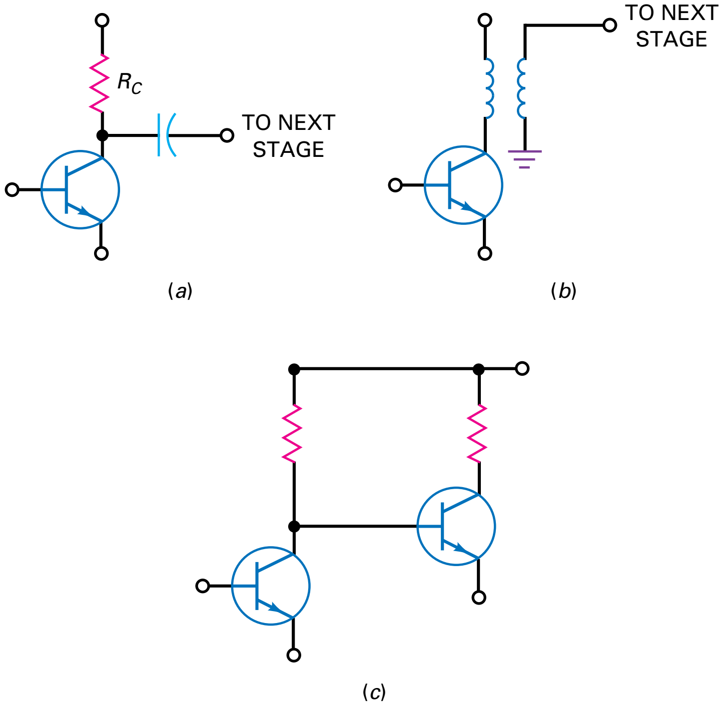


Figure 12-2 Types of coupling: (*a*) capacitive; (*b*) transformer; (*c*) direct.



Because of this, both the dc and the ac voltages are coupled. Since there is no lower frequency limit, a direct-coupled amplifier is sometimes called a *dc amplifier.*

Ranges of Frequency

Another way to describe amplifiers is by stating their frequency range. For instance, an **audio amplifier** refers to an amplifier that operates in the range of 20 Hz to 20 kHz. On the other hand, a **radio-frequency (RF) amplifier** is one that amplifies frequencies above 20 kHz, usually much higher. For instance, the RF amplifiers in AM radios amplify frequencies between 535 and 1605 kHz, and the RF amplifiers in FM radios amplify frequencies between 88 and 108 MHz.

Amplifiers are also classified as **narrowband** or **wideband.** A narrowband amplifier works over a small frequency range like 450 to 460 kHz. A wideband amplifier operates over a large frequency range like 0 to 1 MHz.

Narrowband amplifiers are usually **tuned RF amplifiers,** which means that their ac load is a high-Q resonant tank tuned to a radio station or television channel. Wideband amplifiers are usually untuned; that is, their ac load is resistive.

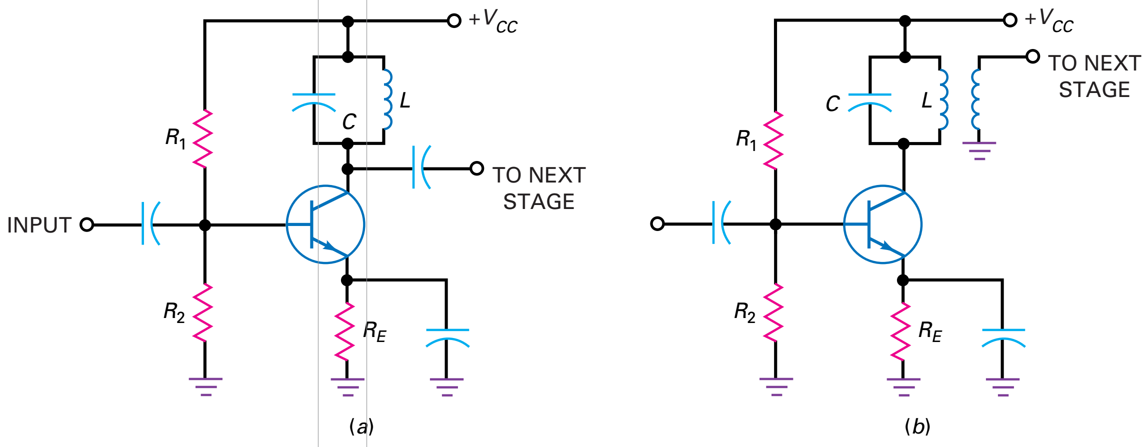
Figure 12-3*a* is an example of a tuned RF amplifier. The *LC* tank is resonant at some frequency. If the tank has a high Q, the bandwidth is narrow. The output is capacitively coupled to the next stage.

Figure 12-3*b* is another example of a tuned RF amplifier. This time, the narrowband output signal is transformer-coupled to the next stage.

Signal Levels

We have already described *small-signal operation,* in which the peak-to-peak swing in collector current is less than 10 percent of quiescent collector current. In **large-signal operation,** a peak-to-peak signal uses all or most of the load line. In a stereo system, the small signal from a radio tuner, tape player, or compact disc

Figure 12-3 Tuned RF amplifiers: (*a*) capacitive coupling; (*b*) transformer coupling.



player is used as the input to a **preamp,** an amplifier that produces a larger output suitable for driving tone and volume controls. The signal is then used as the input to a **power amplifier,** which produces output power ranging from a few hundred milliwatts up to hundreds of watts.

In the remainder of this chapter, we will discuss power amplifiers and related topics like the ac load line, power gain, and efficiency.

12-2 Two Load Lines

Every amplifier has a dc equivalent circuit and an ac equivalent circuit. Because of this, it has two load lines: a dc load line and an ac load line. For small-signal operation, the location of the Q point is not critical. But with large-signal amplifiers, the Q point has to be at the middle of the ac load line to get the maximum possible output swing.

DC Load Line

Figure 12-4*a* is a voltage-divider-based (VDB) amplifier. One way to move the Q point is by varying the value of R_2. For very large values of R_2, the transistor goes into saturation and its current is given by:

$$I_{C(\text{sat})} = \frac{V_{CC}}{R_C + R_E} \tag{12-1}$$

Very small values of R_2 will drive the transistor into cutoff, and its voltage is given by:

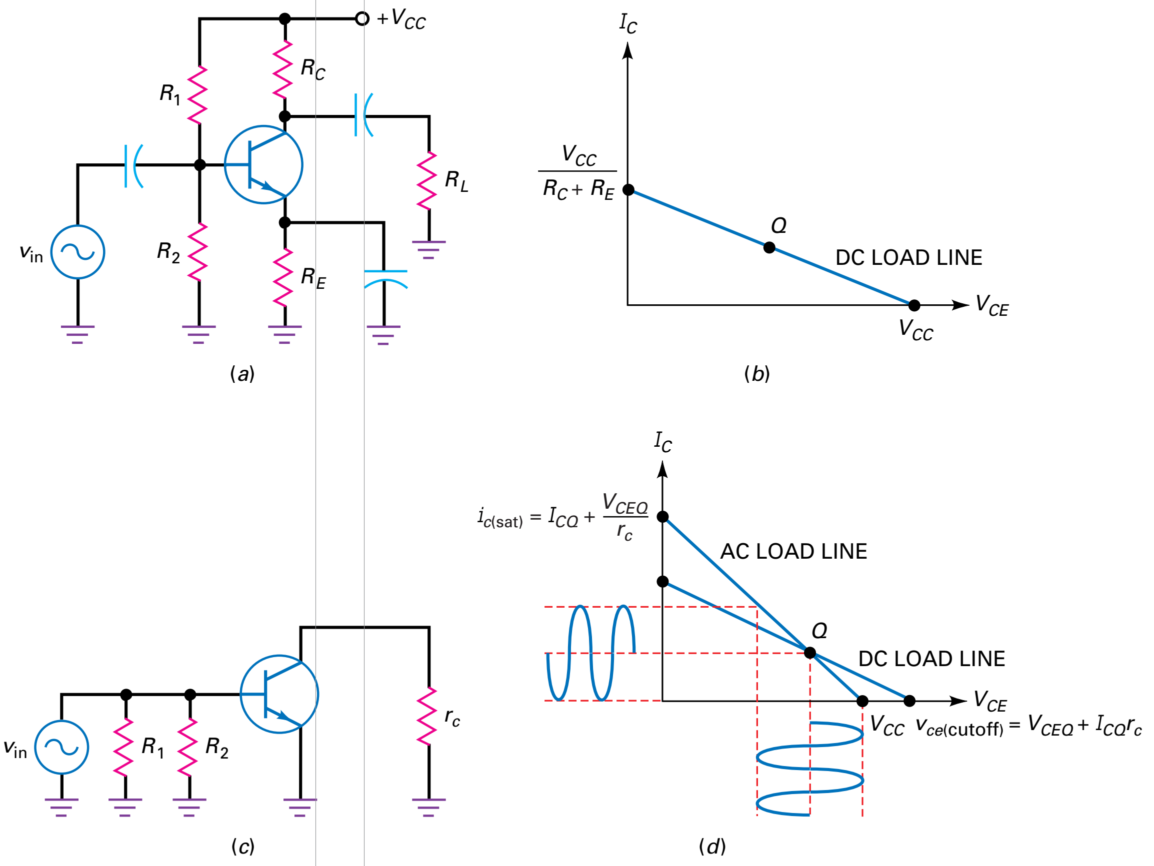
$$V_{CE(\text{cutoff})} = V_{CC} \tag{12-2}$$

Figure 12-4*b* shows the dc load line with the Q point.

AC Load Line

Figure 12-4*c* is the ac equivalent circuit for the VDB amplifier. With the emitter at ac ground, R_E has no effect on the ac operation. Furthermore, the ac collector resistance is less than the dc collector resistance. Therefore, when an ac signal comes in, the instantaneous operating point moves along the **ac load line** of Fig. 12-4*d*. In other words, the peak-to-peak sinusoidal current and voltage are determined by the ac load line.

Figure 12-4 (*a*) VDB amplifier; (*b*) dc load line; (*c*) ac equivalent circuit; (*d*) ac load line.



As shown in Fig. 12-4*d*, the saturation and cutoff points on the ac load line differ from those on the dc load line. Because the ac collector and emitter resistance are lower than the respective dc resistance, the ac load line is much steeper. It's important to note that the ac and dc load lines intersect at the *Q* point. This happens when the ac input voltage is crossing zero.

Here's how to determine the ends of the ac load line. Writing a collector voltage loop gives us:

$$v_{ce} + i_c r_c = 0$$

or

$$\boldsymbol{i_c = -\frac{v_{ce}}{r_c}} \qquad \textbf{(12-3)}$$

The ac collector current is given by:

$$i_c = \Delta I_C = I_C - I_{CQ}$$

and the ac collector voltage is:

$$v_{ce} = \Delta V_{CE} = V_{CE} - V_{CEQ}$$

When substituting these expressions into Eq. (12-3) and rearranging, we arrive at:

$$\boldsymbol{I_C = I_{CQ} + \frac{V_{CEQ}}{r_c} - \frac{V_{CE}}{r_c}} \qquad \textbf{(12-4)}$$

This is the equation of the ac load line. When the transistor goes into saturation, V_{CE} is zero, and Eq. (12-4) gives us:

$$\boldsymbol{i_{c(\text{sat})} = I_{CQ} + \frac{V_{CEQ}}{r_c}} \qquad \textbf{(12-5)}$$

where $i_{c(\text{sat})}$ = ac saturation current
I_{CQ} = dc collector current
V_{CEQ} = dc collector-emitter voltage
r_c = ac resistance seen by the collector

When the transistor goes into cutoff, I_c equals zero. Since

$$v_{ce(\text{cutoff})} = V_{CEQ} + \Delta V_{CE}$$

and

$$\Delta V_{CE} = (\Delta I_C)(r_c)$$

we can substitute to get

$$\Delta V_{CE} = (I_{CQ} - OA)(r_c)$$

resulting in

$$\boldsymbol{v_{ce(\text{cutoff})} = V_{CEQ} + I_{CQ}r_c} \qquad \textbf{(12-6)}$$

Because the ac load line has a higher slope than the dc load line, the maximum peak-to-peak (MPP) output is always less than the supply voltage. As a formula:

$$\textbf{MPP} < \boldsymbol{V_{CC}} \qquad \textbf{(12-7)}$$

For instance, if the supply voltage is 10 V, the maximum peak-to-peak sinusoidal output is less than 10 V.

Clipping of Large Signals

When the Q point is at the center of the dc load line (Fig. 12-4*d*), the ac signal cannot use all of the ac load line without clipping. For instance, if the ac signal increases, we will get the cutoff clipping shown in Fig. 12-5*a*.

If the Q point is moved higher as shown in Fig. 12-5*b*, a large signal will drive the transistor into saturation. In this case, we get saturation clipping. Both cutoff and saturation clipping are undesirable because they distort the signal. When a distorted signal like this drives a loudspeaker, it sounds terrible.

A well-designed large-signal amplifier has the Q point at the middle of the ac load line (Fig. 12-5*c*). In this case, we get a maximum peak-to-peak unclipped output. This maximum unclipped peak-to-peak ac voltage is also referred to its ac output compliance.

Maximum Output

When the Q point is below the center of the ac load line, the maximum peak (MP) output is $I_{CQ}r_c$, as shown in Fig. 12-6*a*. On the other hand, if the Q point is above the center of the ac load line, the maximum peak output is V_{CEQ}, as shown in Fig. 12-6*b*.

For any Q point, therefore, the maximum peak output is:

$$\textbf{MP} = \boldsymbol{I_{CQ}r_c} \quad \textbf{or} \quad \boldsymbol{V_{CEQ},} \quad \text{whichever is smaller} \qquad \textbf{(12-8)}$$

and the maximum peak-to-peak output is twice this amount:

$$\textbf{MPP = 2MP} \qquad \textbf{(12-9)}$$

Equations (12-8) and (12-9) are useful in troubleshooting to determine the largest unclipped output that is possible.

Figure 12-5 (*a*) Cutoff clipping; (*b*) saturation clipping; (*c*) optimum *Q* point.

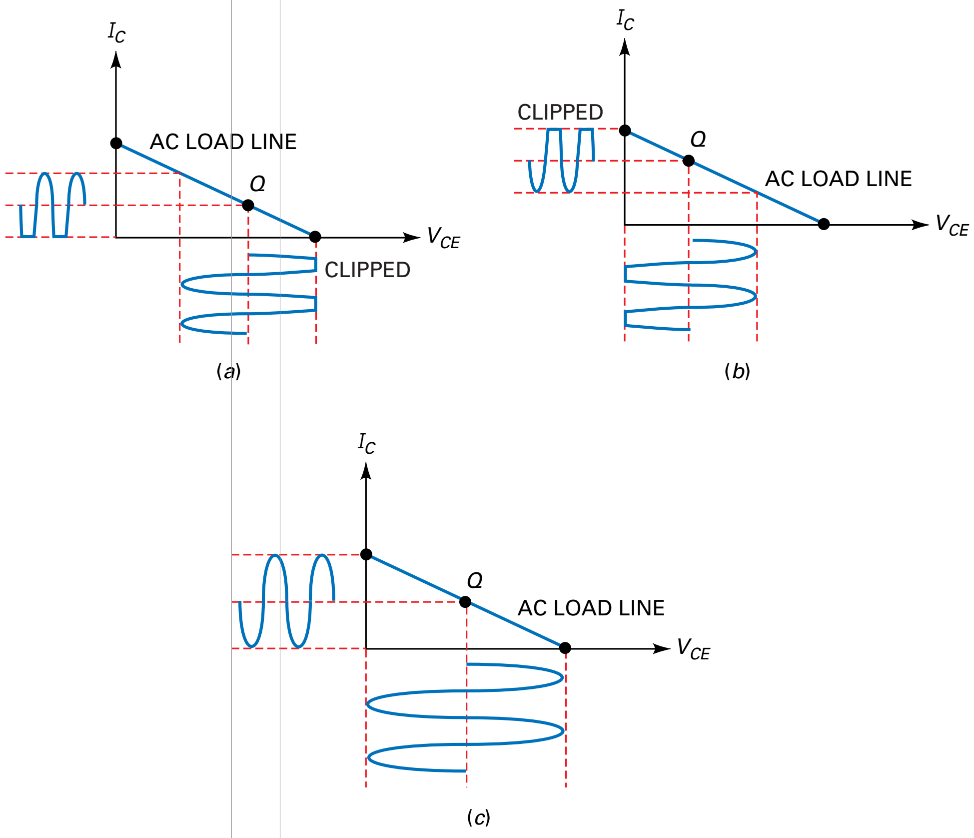
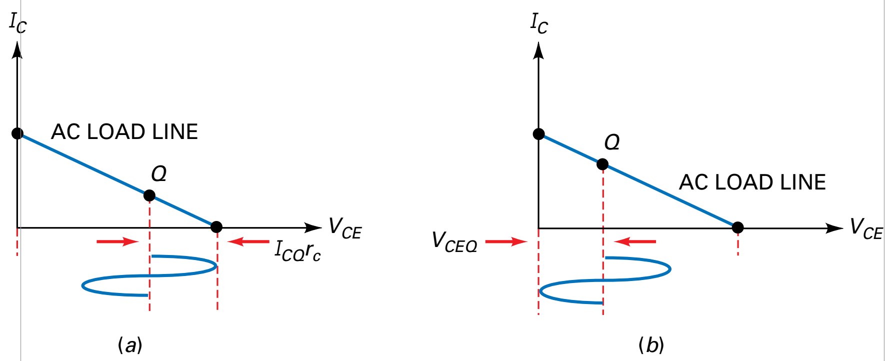


Figure 12-6 *Q* point at center of ac load line.



When the *Q* point is at the center of the ac load line:

$$I_{CQ}r_c = V_{CEQ} \tag{12-10}$$

A designer will try to satisfy this condition as closely as possible, given the tolerance of biasing resistors. The circuit's emitter resistance can be adjusted to find the optimum *Q* point. A formula that can be derived for the optimum emitter resistance is:

$$R_E = \frac{R_C + r_c}{V_{CC}/V_E - 1} \tag{12-11}$$

Example 12-1

What are the values of I_{CQ}, V_{CEQ} and r_c in Fig. 12-7?

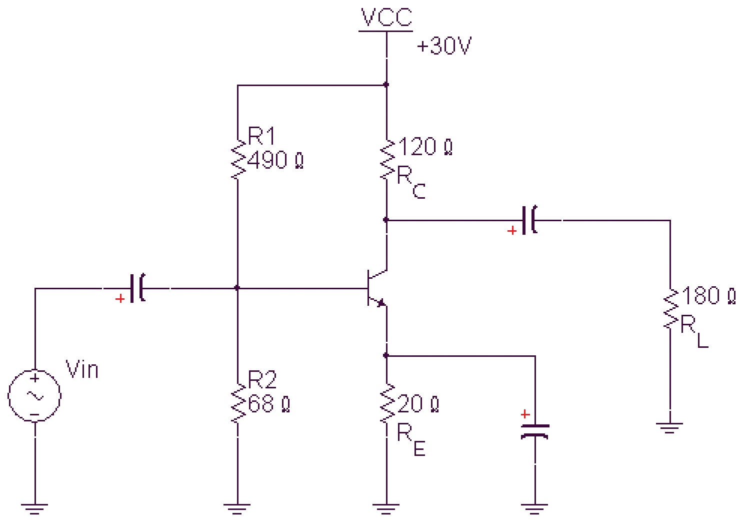


Figure 12-7 Example.

SOLUTION

$$V_B = \frac{68\ \Omega}{68\ \Omega + 490\ \Omega}(30\ \text{V}) = 3.7\ \text{V}$$

$$V_E = V_B - 0.7\ \text{V} = 3.7\ \text{V} - 0.7\ \text{V} = 3\ \text{V}$$

$$I_E = \frac{V_E}{R_E} = \frac{3\ \text{V}}{20\ \Omega} = 150\ \text{mA}$$

$$I_{CQ} \cong I_E = 150\ \text{mA}$$

$$V_{CEQ} = V_C - V_E = 12\ \text{V} - 3\ \text{V} = 9\ \text{V}$$

$$r_c = R_C \| R_L = 120\ \Omega \| 180\ \Omega = 72\ \Omega$$

PRACTICE PROBLEM 12-1 In Fig. 12-7, change R_E from 20 Ω to 30 Ω. Solve for I_{CQ} and V_{CEQ}.

Example 12-2

Determine the ac load line saturation and cutoff points in Fig. 12-7. Also, find the maximum peak-to-peak output voltage.

SOLUTION From Example 12-1, the transistor's Q point is:

$$I_{CQ} = 150\ \text{mA} \quad \text{and} \quad V_{CEQ} = 9\ \text{V}$$

To find the ac saturation and cutoff points, first determine the ac collector resistance, r_c:

$$r_c = R_C \| R_L = 120\ \Omega \| 180\ \Omega = 72\ \Omega$$

Next find the ac load line end points:

$$i_{c(\text{sat})} = I_{CQ} + \frac{V_{CEQ}}{r_c} = 150\ \text{mA} + \frac{9\ \text{V}}{72\ \Omega} = 275\ \text{mA}$$

$$v_{ce(\text{cutoff})} = V_{CEQ} + I_{CQ}r_c = 9\ \text{V} + (150\ \text{mA})(72\ \Omega) = 19.8\ \text{V}$$

Now determine the MPP value. With a supply voltage of 30 V:

MPP < 30 V

MP will be the smaller value of

$I_{CQ}r_c = (150\text{ mA})(72\ \Omega) = 10.8\text{ V}$

or

$V_{CEQ} = 9\text{ V}$

Therefore, MPP = 2 (9 V) = 18 V

PRACTICE PROBLEM 12-2 Using Example 12-2, change R_E to 30 Ω and find $i_{c(\text{sat})}$, $v_{ce(\text{cutoff})}$, and MPP.

12-3 Class A Operation

The VDB amplifier of Fig. 12-8*a* is a class A amplifier as long as the output signal is not clipped. With this kind of amplifier, collector current flows throughout the cycle. Stated another way, no clipping of the output signal occurs at any time during the cycle. Now, we discuss a few equations that are useful in the analysis of class A amplifiers.

GOOD TO KNOW

The power gain A_P of a common-emitter amplifier equals $A_V \times A_i$. Since A_i can be expressed as $A_i = A_V \times Z_{in}/R_L$, then A_P can be expressed as $A_P = A_V \times A_V \times Z_{in}/R_L$ or $A_P = A^2{}_V \times Z_{in}/R_L$.

Power Gain

Besides voltage gain, any amplifier has a **power gain,** defined as:

$$A_p = \frac{p_{out}}{p_{in}} \tag{12-12}$$

In words, the power gain equals the ac output power divided by the ac input power.

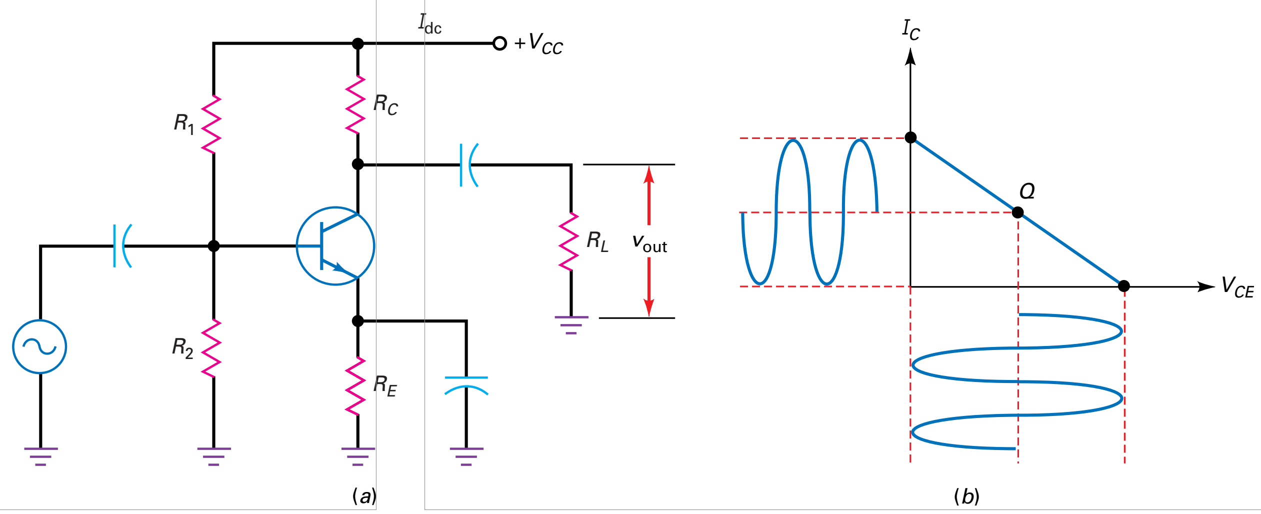


Figure 12-8 Class A amplifier.

For instance, if the amplifier of Fig. 12-8*a* has an output power of 10 mW and an input power of 10 μW, it has a power gain of:

$$A_p = \frac{10\text{ mW}}{10\ \mu\text{W}} = 1000$$

Output Power

If we measure the output voltage of Fig. 12-8*a* in rms volts, the output power is given by

$$p_{out} = \frac{v_{rms}^2}{R_L} \tag{12-13}$$

Usually, we measure the output voltage in peak-to-peak volts with an oscilloscope. In this case, a more convenient equation to use for output power is:

$$p_{out} = \frac{v_{out}^2}{8R_L} \tag{12-14}$$

The factor of 8 in the denominator occurs because $v_{pp} = 2\sqrt{2}\ v_{rms}$. When you square $2\sqrt{2}$, you get 8.

The maximum output power occurs when the amplifier is producing the maximum peak-to-peak output voltage, as shown in Fig. 12-8*b*. In this case, v_{pp} equals the maximum peak-to-peak output voltage and the maximum output power is:

$$p_{out(max)} = \frac{MPP^2}{8R_L} \tag{12-15}$$

Transistor Power Dissipation

When no signal drives the amplifier of Fig. 12-8*a*, the quiescent power dissipation is:

$$P_{DQ} = V_{CEQ}I_{CQ} \tag{12-16}$$

This makes sense. It says that the quiescent power dissipation equals the dc voltage times the dc current.

When a signal is present, the power dissipation of a transistor decreases because the transistor converts some of the quiescent power to signal power. For this reason, the quiescent power dissipation is the worst case. Therefore, the power rating of a transistor in a class A amplifier must be greater than P_{DQ}; otherwise, the transistor will be destroyed.

Current Drain

As shown in Fig. 12-8*a*, the dc voltage source has to supply a dc current I_{dc} to the amplifier. This dc current has two components: the biasing current through the voltage divider and the collector current through the transistor. The dc current is called the **current drain** of the stage. If you have a multistage amplifier, you have to add the individual current drains to get the total current drain.

Efficiency

The dc power supplied to an amplifier by the dc source is:

$$P_{dc} = V_{CC}I_{dc} \tag{12-17}$$

To compare the design of power amplifiers, we can use the **efficiency,** defined by:

$$\eta = \frac{p_{out}}{P_{dc}} \times 100\% \tag{12-18}$$

GOOD TO KNOW

Efficiency can also be defined as the amplifier's ability to convert its dc input power to useful ac output power.

This equation says that the efficiency equals the ac output power divided by the dc input power.

The efficiency of any amplifier is between 0 and 100 percent. Efficiency gives us a way to compare two different designs because it indicates how well an amplifier converts the dc input power to ac output power. The higher the efficiency, the better the amplifier is at converting dc power to ac power. This is important in battery-operated equipment because high efficiency means that the batteries last longer.

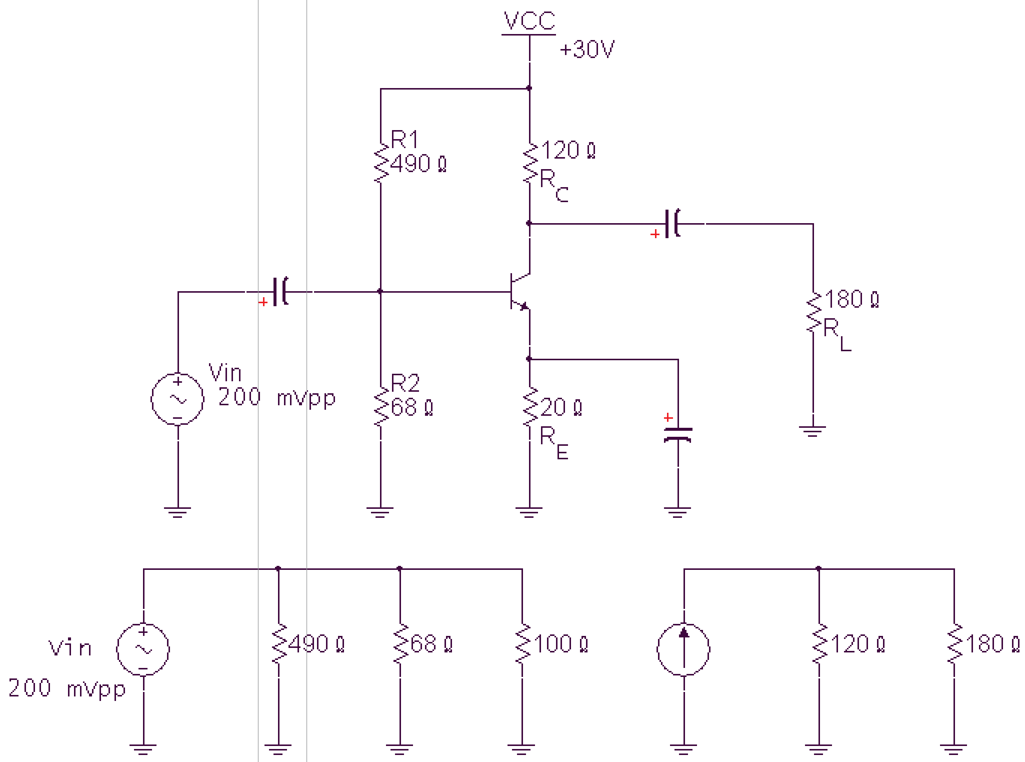
Since all resistors except the load resistor waste power, the efficiency is less than 100 percent in a class A amplifier. In fact, it can be shown that the maximum efficiency of a class A amplifier with a dc collector resistance and a separate load resistance is 25 percent.

In some applications, the low efficiency of class A is acceptable. For instance, the small-signal stages near the front of a system usually work fine with low efficiency because the dc input power is small. In fact, if the final stage of a system needs to deliver only a few hundred milliwatts, the current drain on the power supply may still be low enough to accept. But when the final stage needs to deliver watts of power, the current drain usually becomes too large with class A operation.

Example 12-3

If the peak-to-peak output voltage is 18 V and the input impedance of the base is 100 Ω, what is the power gain in Fig. 12-9*a*?

Figure 12-9 Example



SOLUTION As shown in Fig. 12-9*b*:

$$z_{in(stage)} = 490\ \Omega \parallel 68\ \Omega \parallel 100\ \Omega = 37.4\ \Omega$$

The ac input power is:

$$P_{in} = \frac{(200\ \text{mV})^2}{8\ (37.4)} = 133.7\ \mu\text{W}$$

The ac output power is:

$$P_{out} = \frac{(18\ \text{V})^2}{8\ (180\ \Omega)} = 225\ \text{mW}$$

The power gain is:

$$A_p = \frac{225\ \text{mW}}{133.7\ \mu\text{W}} = 1{,}683$$

PRACTICE PROBLEM 12-3 In Fig. 12-9*a*, if R_L is 120 Ω and the peak-to-peak output voltage equals 12 V, what is the power gain?

Example 12-4

What is the transistor power dissipation and efficiency of Fig. 12-9*a*?

SOLUTION The dc emitter current is:

$$I_E = \frac{3\ \text{V}}{20\ \Omega} = 150\ \text{mA}$$

The dc collector voltage is:

$$V_C = 30\ \text{V} - (150\ \text{mA})(120\ \Omega) = 12\ \text{V}$$

and the dc collector-emitter voltage is:

$$V_{CEQ} = 12\ \text{V} - 3\ \text{V} = 9\ \text{V}$$

The transistor power dissipation is:

$$P_{DQ} = V_{CEQ}\, I_{CQ} = (9\ \text{V})(150\ \text{mA}) = 1.35\ \text{W}$$

To find the stage efficiency:

$$I_{bias} = \frac{30\ \text{V}}{490\ \Omega + 68\ \Omega} = 53.8\ \text{mA}$$

$$I_{dc} = I_{bias} + I_{CQ} = 53.8\ \text{mA} + 150\ \text{mA} = 203.8\ \text{mA}$$

The dc input power to the stage is:

$$P_{dc} = V_{CC} I_{dc} = (30\ \text{V})(203.8\ \text{mA}) = 6.11\ \text{W}$$

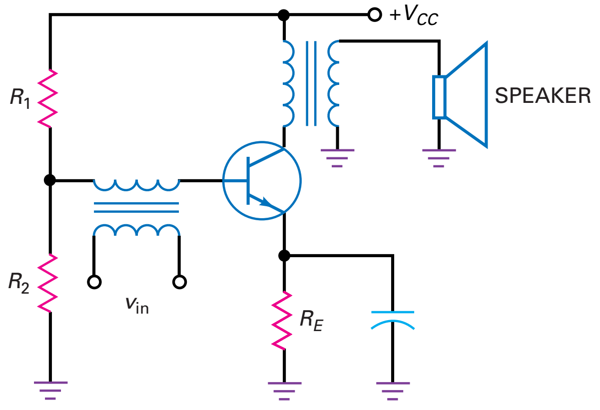
Since the output power (found in Example 12-3) is 225 mW, the efficiency of the stage is:

$$\eta = \frac{225\ \text{mW}}{6.11\ \text{W}} x\, 100\% = 3.68\%$$

Example 12-5

Describe the action of Fig. 12-10.

Figure 12-10 Class A power amplifier.



SOLUTION This is a class A power amplifier driving a loudspeaker. The amplifier uses voltage-divider bias, and the ac input signal is transformer-coupled to the base. The transistor produces voltage and power gain to drive the loudspeaker through the output transformer.

A small speaker with an impedance of 3.2 Ω needs only 100 mW in order to operate. A slightly larger speaker with an impedance of 8 Ω needs 300 to 500 mW for proper operation. Therefore, a class A power amplifier like Fig. 12-10 may be adequate if all you need is a few hundred milliwatts of output power. Since the load resistance is also the ac collector resistance, the efficiency of this class A amplifier is higher than that of the class A amplifier discussed earlier. Using the impedance-reflecting ability of the transformer, the speaker load resistance appears $\left(\frac{N_P}{N_S}\right)^2$ times larger at the collector. If the transformer's turns ratio were 10:1, a 32 Ω speaker would appear as 320 Ω at the collector.

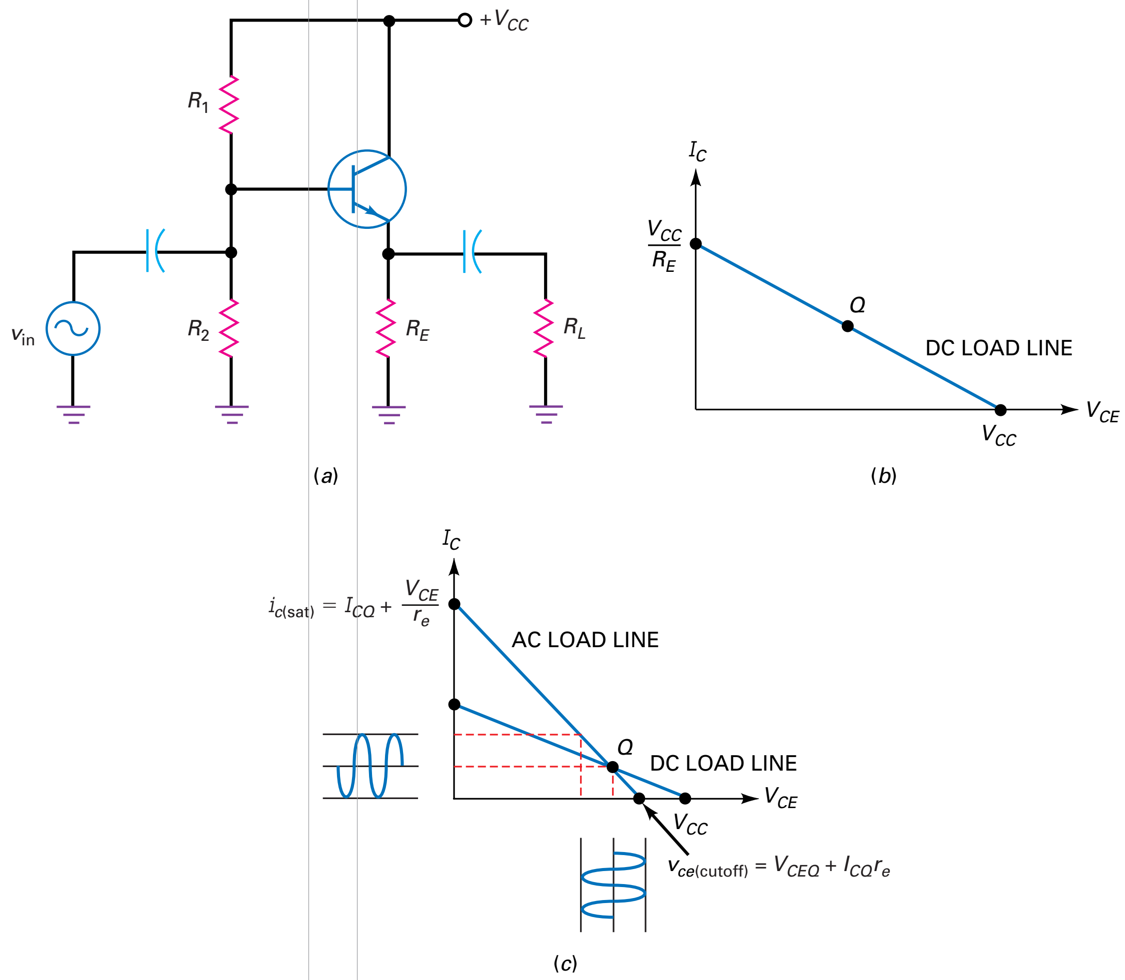
The class A amplifier discussed earlier had a separate collector resistance R_C and a separate load resistance R_L. The best you can do in this case is to match the impedances, $R_L = R_C$, to get a maximum efficiency of 25 percent. When the load resistance becomes the ac collector resistor, as shown in Fig. 12-10, it receives twice as much output power, and the maximum efficiency increases to 50 percent.

PRACTICE PROBLEM 12-5 In Fig. 12-10, what resistance would an 8 Ω speaker appear to the collector as, if the transformer's turns ratio were 5 : 1?

Emitter-Follower Power Amplifier

When the emitter follower is used as class A power amplifier at the end of a system, a designer will usually locate the Q point at the center of the ac load line to get maximum peak-to-peak (MPP) output.

Figure 12-11 DC and ac load lines.



In Fig. 12-11*a*, large values of R_2 will saturate the transistor, producing a saturation current of:

$$I_{C(sat)} = \frac{V_{CC}}{R_E} \qquad \textbf{(12-19)}$$

Small values of R_2 will drive the transistor into cutoff, producing a cutoff voltage of:

$$V_{CE(cutoff)} = V_{CC} \qquad \textbf{(12-20)}$$

Fig. 12-11*b* shows the dc load line with the *Q* point.

In Fig. 12-11*a*, the ac emitter resistance is less than the dc emitter resistance. Therefore, when an ac signal comes in, the instantaneous operating point moves along the ac load line of Fig. 12-11*c*. The peak-to-peak sinusoidal current and voltage are determined by the ac load line.

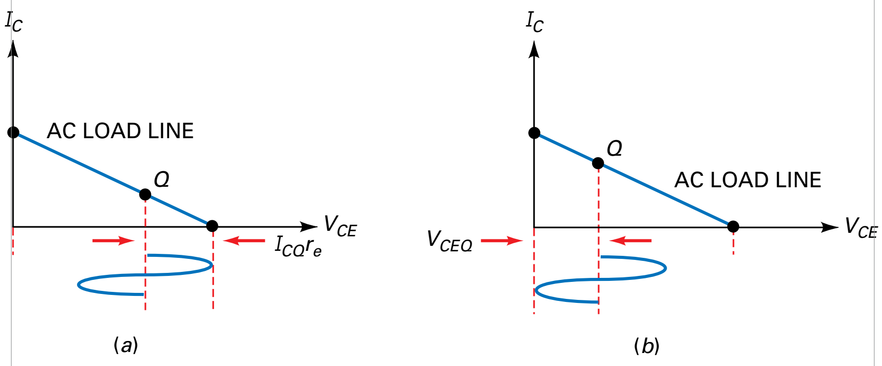
As shown in Fig. 12-11*c*, the ac load line end points are found by:

$$i_{c(sat)} = I_{CQ} + \frac{V_{CE}}{r_e} \qquad \textbf{(12-21)}$$

and

$$V_{CE(cutoff)} = V_{CE} + I_{CQ}\, r_e \qquad \textbf{(12-22)}$$

Figure 12-12 Maximum peak excursions.



Because the ac load line has a higher slope than the dc load line, the maximum peak-to-peak output is always less than the supply voltage. As with the class A CE amplifier, MPP $< V_{CC}$.

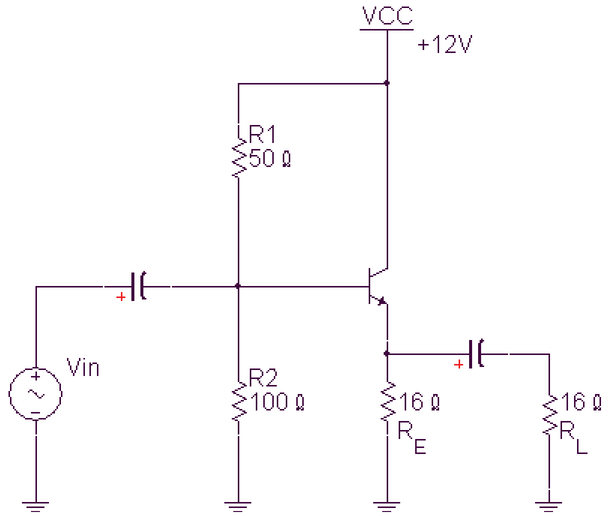
When the Q point is below the center of the ac load line, the maximum peak (MP) output is $I_{CQ}r_e$, as shown in Fig. 12-12*a*. On the other hand, if the Q point is above the center of the load line, the maximum peak output is V_{CEQ}, as shown in Fig. 12-12*b*.

As you can see, determining the MPP value for an emitter-follower amplifier is essentially the same as for a CE amplifier. The difference is the need to use the emitter ac resistance, r_e, instead of the collector ac resistance, r_c. To increase the output power level, the emitter follower may also be connected in a Darlington configuration.

Example 12-6

What are the values of I_{CQ}, V_{CEQ}, and r_e in Fig. 12-13?

Figure 12-13 Emitter-Follower power amplifier.



SOLUTION

$$I_{CQ} = \frac{8 \text{ V} - 0.7 \, v}{16 \, \Omega} = 456 \text{ mA}$$

$$V_{CEQ} = 12 \text{ V} - 7.3 \text{ V} = 4.7 \text{ V}$$

and

$$r_e = 16 \, \Omega \parallel 16 \, \Omega = 8 \, \Omega$$

PRACTICE PROBLEM 12-6 In Fig. 12-13, change R_1 to 100 Ω and find I_{CQ}, V_{CEQ}, and r_e.

Example 12-7

Determine the ac saturation and cutoff points in Fig. 12-13. Also, find the circuit's MPP output voltage.

SOLUTION From Example 12-6, the dc Q point is:

$$I_{CQ} = 456 \text{ mA} \quad \text{and} \quad V_{CEQ} = 4.7 \text{ V}$$

The ac load line saturation and cutoff points are found by:

$$r_e = R_C \parallel R_L = 16 \, \Omega \parallel 16 \, \Omega = 8 \, \Omega$$

$$i_{c(\text{sat})} = I_{CQ} + \frac{V_{CE}}{r_e} = 456 \text{ mA} + \frac{4.7 \text{ V}}{8 \, \Omega} = 1.04 \text{ A}$$

$$v_{ce(\text{cutoff})} = V_{CEQ} + I_{CQ}r_e = 4.7 \text{ V} + (456 \text{ mA})(8 \, \Omega) = 8.35 \text{ V}$$

MPP is found by determining the smaller value of:

$$\text{MPP} = I_{CQ}r_e = (456 \text{ mA})(8 \, \Omega) = 3.65 \text{ V}$$

or

$$\text{MP} = V_{CEQ} = 4.7 \text{ V}$$

Therefore, MPP = 2 (3.65 V) = 7.3 V_{pp}.

PRACTICE PROBLEM 12-7 In Fig. 12-13, if R_1 = 100 Ω, solve for its MPP value.

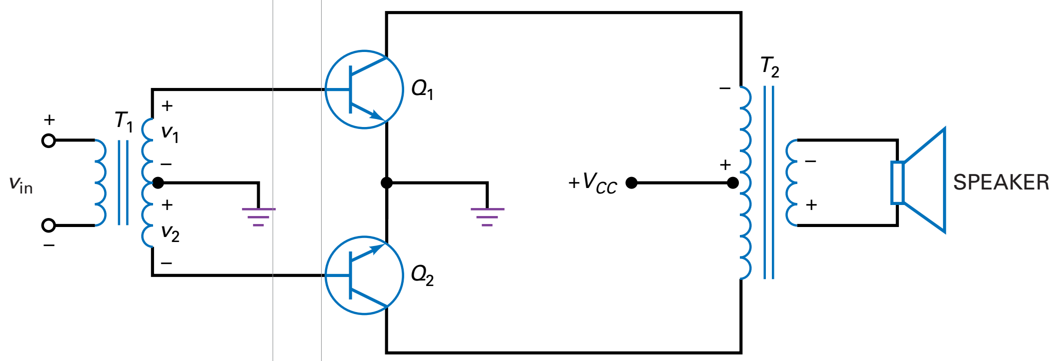
12-4 Class B Operation

Class A is the common way to run a transistor in linear circuits because it leads to the simplest and most stable biasing circuits. But class A is not the most efficient way to operate a transistor. In some applications, like battery-powered systems, current drain and stage efficiency become important considerations in the design. This section introduces the basic idea of class B operation.

Push-Pull Circuit

Figure 12-14 shows a basic class B amplifier. When a transistor operates as class B, it clips off half a cycle. To avoid the resulting distortion, we can use two

Figure 12-14 Class B push-pull amplifier.



transistors in a push-pull arrangement like that of Fig. 12-14. **Push-pull** means that one transistor conducts for half a cycle while the other is off, and vice versa.

Here is how the circuit works: On the positive half cycle of input voltage, the secondary winding of T_1 has voltage v_1 and v_2, as shown. Therefore, the upper transistor conducts and the lower one cuts off. The collector current through Q_1 flows through the upper half of the output primary winding. This produces an amplified and inverted voltage, which is transformer-coupled to the loudspeaker.

On the next half cycle of input voltage, the polarities reverse. Now, the lower transistor turns on and the upper transistor turns off. The lower transistor amplifies the signal, and the alternate half cycle appears across the loudspeaker.

Since each transistor amplifies one-half of the input cycle, the loudspeaker receives a complete cycle of the amplified signal.

Advantages and Disadvantages

Since there is no bias in Fig. 12-14, each transistor is at cutoff when there is no input signal, an advantage because there is no current drain when the signal is zero.

Another advantage is improved efficiency where there is an input signal. The maximum efficiency of a class B push-pull amplifier is 78.5 percent, so a class B push-pull power amplifier is more commonly used for an output stage than a class A power amplifier.

The main disadvantage of the amplifier shown in Fig. 12-14 is the use of transformers. Audio transformers are bulky and expensive. Although widely used at one time, a transformer-coupled amplifier like Fig. 12-14 is no longer popular. Newer designs have eliminated the need for transformers in most applications.

12-5 Class B Push-Pull Emitter Follower

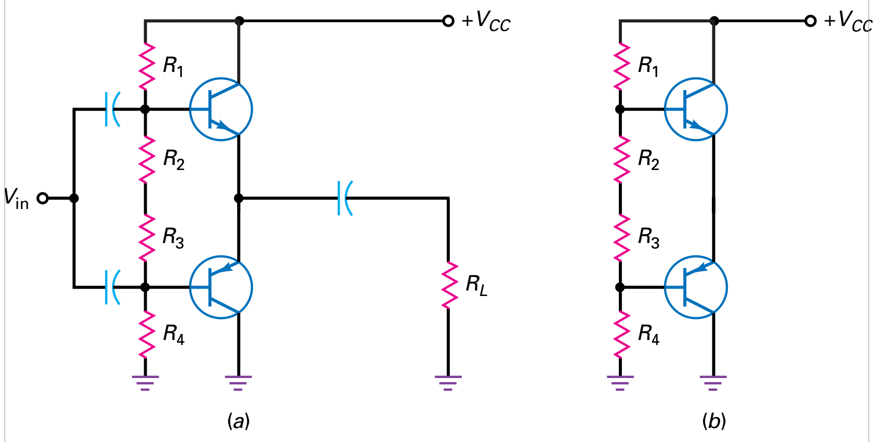
Class B operation means that the collector current flows for only 180° of the ac cycle. For this to occur, the Q point is located at cutoff on both the dc and the ac load lines. The advantage of class B amplifiers is lower current drain and higher stage efficiency.

Push-Pull Circuit

Figure 12-15*a* shows one way to connect a class B push-pull emitter follower. Here, we have an *npn* emitter follower and a *pnp* emitter follower connected in a push-pull arrangement.

Let's begin the analysis with the dc equivalent circuit of Fig. 12-15*b*. The designer selects biasing resistors to set the Q point at cutoff. This biases the

Figure 12-15 Class B push-pull emitter follower: (*a*) complete circuit; (*b*) dc equivalent circuit.



emitter diode of each transistor between 0.6 and 0.7 V, so that it is on the verge of conduction. Ideally:

$$I_{CQ} = 0$$

Because the biasing resistors are equal, each emitter diode is biased with the same value of voltage. As a result, half the supply voltage is dropped across each transistor's collector-emitter terminals. That is:

$$V_{CEQ} = \frac{V_{CC}}{2} \tag{12-23}$$

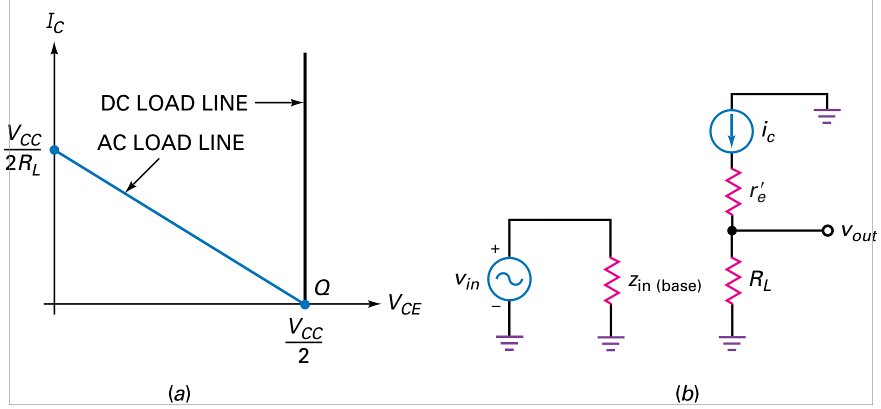
DC Load Line

Since there is no dc resistance in the collector or emitter circuits of Fig. 12-15*b*, the dc saturation current is infinite. This means that the dc load line is vertical, as shown in Fig. 12-16*a*. If you think that this is a dangerous situation, you are right. The most difficult thing about designing a class B amplifier is setting up a stable Q point at cutoff. Any significant decrease in V_{BE} with temperature can move the Q point up the dc load line to dangerously high currents. For the moment, assume that the Q point is rock-solid at cutoff, as shown in Fig. 12-16*a*.

AC Load Line

Figure 12-16*a* shows the ac load line. When either transistor is conducting, its operating point moves up along the ac load line. The voltage swing of the

Figure 12-16 (*a*) DC and ac load lines; (*b*) ac equivalent circuit.



conducting transistor can go all the way from cutoff to saturation. On the alternate half cycle, the other transistor does the same thing. This means that the maximum peak-to-peak output is:

$$\text{MPP} = V_{CC} \tag{12-24}$$

AC Analysis

Figure 12-16*b* shows the ac equivalent of the conducting transistor. This is almost identical to the class A emitter follower. Ignoring r'_e, the voltage gain is:

$$A \approx 1 \tag{12-25}$$

and the input impedance of the base is:

$$z_{\text{in(base)}} \approx \beta R_L \tag{12-26}$$

Overall Action

On the positive half cycle of input voltage, the upper transistor of Fig. 12-15*a* conducts and the lower one cuts off. The upper transistor acts like an ordinary emitter follower, so that the output voltage approximately equals the input voltage.

On the negative half cycle of input voltage, the upper transistor cuts off and the lower transistor conducts. The lower transistor acts like an ordinary emitter follower and produces a load voltage approximately equal to the input voltage. The upper transistor handles the positive half cycle of input voltage, and the lower transistor takes care of the negative half cycle. During either half cycle, the source sees a high input impedance looking into either base.

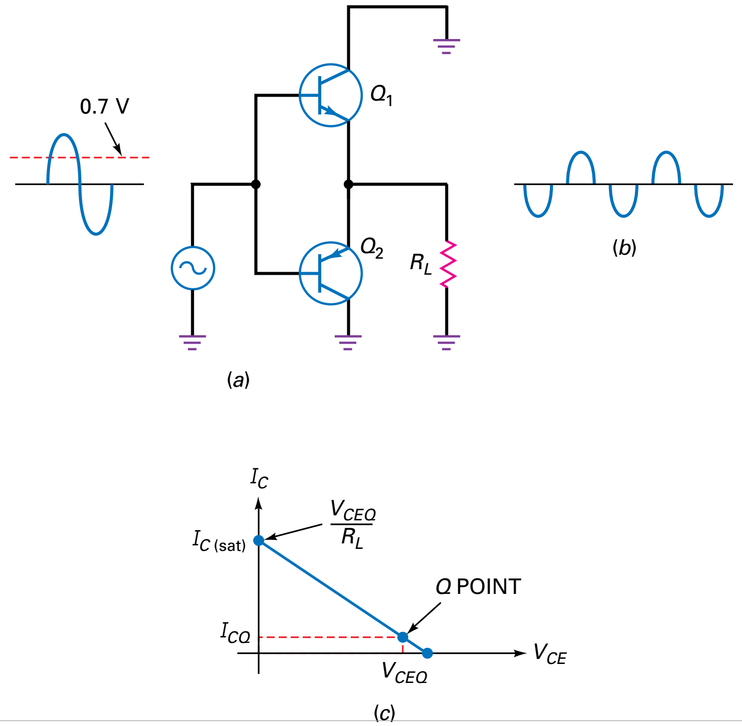
GOOD TO KNOW

Some power amplifiers are biased to operate as class AB amplifiers to improve the linearity of the output signal. A class AB amplifier has a conduction angle of roughly 210°. The improved linearity of the output signal does not come without a price, however—a reduction in the circuit's efficiency.

Crossover Distortion

Figure 12-17*a* shows the ac equivalent circuit of a class B push-pull emitter follower. Suppose that no bias is applied to the emitter diodes. Then, the incoming ac

Figure 12-17 (*a*) AC equivalent circuit; (*b*) crossover distortion; (*c*) *Q* point is slightly above cutoff.



voltage has to rise to about 0.7 V to overcome the barrier potential of the emitter diodes. Because of this, no current flows through Q_1 when the signal is less than 0.7 V.

The action is similar on the other half cycle. No current flows through Q_2 until the ac input voltage is more negative than −0.7 V. For this reason, if no bias is applied to the emitter diodes, the output of a class B push-pull emitter follower looks like Fig. 12-17*b*.

Because of clipping between half cycles, the output is distorted. Since the clipping occurs between the time one transistor cuts off and the other one comes on, we call it **crossover distortion.** To eliminate crossover distortion, we need to apply a slight forward bias to each emitter diode. This means locating the Q point slightly above cutoff, as shown in Fig. 12-17*c*. As a guide, an I_{CQ} from 1 to 5 percent of $I_{C(sat)}$ is enough to eliminate crossover distortion.

Class AB

In Fig. 12-17*c*, the slight forward bias implies that the conduction angle will be slightly greater than 180° because the transistor will conduct for a bit more than half a cycle. Strictly speaking, we no longer have class B operation. Because of this, the operation is sometimes referred to as **class AB,** defined as a conduction angle between 180° and 360°. But it is barely class AB. For this reason, many people still refer to the circuit as a *class B push-pull amplifier* because the operation is class B to a close approximation.

Power Formulas

The formulas shown in Table 12-1 apply to all classes of operation including class B push-pull operation.

When using these formulas to analyze a class B/AB push-pull emitter follower, remember that the class B/AB push-pull amplifier has the ac load line and waveforms of Fig. 12-18*a*. Each transistor supplies half of a cycle.

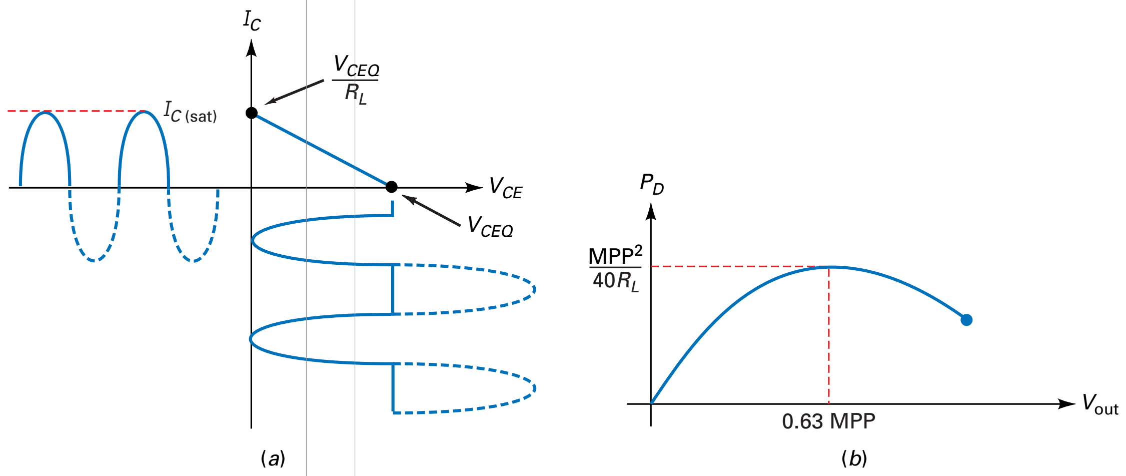
Transistor Power Dissipation

Ideally, the transistor power dissipation is zero when there is no input signal because both transistors are cut off. If there is a slight forward bias to prevent crossover distortion, the quiescent power dissipation in each transistor is still very small.

Table 12-1 Amplifier Power Formulas

Equation	Value
$A_p = \dfrac{p_{out}}{p_{in}}$	Power gain
$p_{out} = \dfrac{v_{out}^2}{8R_L}$	AC output power
$p_{out(max)} = \dfrac{MPP^2}{8R_L}$	Maximum ac output power
$P_{dc} = V_{CC}I_{dc}$	DC input power
$\eta = \dfrac{p_{out}}{P_{dc}} \times 100\%$	Efficiency

Figure 12-18 (a) Class B load line; (b) transistor power dissipation.



When an input signal is present, the transistor power dissipation becomes significant. The transistor power dissipation depends on how much of the ac load line is used. The maximum transistor power dissipation of each transistor is:

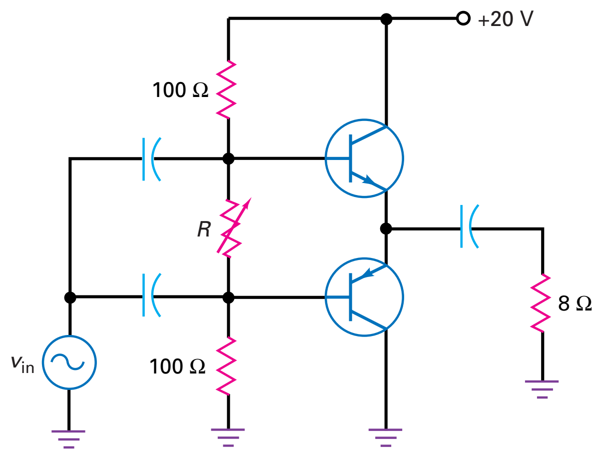
$$P_{D(max)} = \frac{MPP^2}{40R_L} \quad (12\text{-}27)$$

Figure 12-18*b* shows how the transistor power dissipation varies according to the peak-to-peak output voltage. As indicated, P_D reaches a maximum when the peak-to-peak output is 63 percent of MPP. Since this is the worst case, each transistor in a class B/AB push-pull amplifier must have a power rating of at least $MPP^2/40R_L$.

Example 12-8

The adjustable resistor of Fig. 12-19 sets both emitter diodes on the verge of conduction. What is the maximum transistor power dissipation? The maximum output power?

Figure 12-19 Example.



SOLUTION The maximum peak-to-peak output is:

$$\text{MPP} = V_{CC} = 20 \text{ V}$$

With Eq. (12-18):

$$P_{D(\max)} = \frac{\text{MPP}^2}{40R_L} = \frac{(20 \text{ V})^2}{40(8\ \Omega)} = 1.25 \text{ W}$$

The maximum output power is:

$$p_{\text{out(max)}} = \frac{\text{MPP}^2}{8R_L} = \frac{(20 \text{ V})^2}{8(8\ \Omega)} = 6.25 \text{ W}$$

PRACTICE PROBLEM 12-8 In Fig. 12-19, change V_{CC} to +30 V and calculate $P_{D(\max)}$ and $P_{\text{out(max)}}$.

Example 12-9

If the adjustable resistance is 15 Ω, what is the efficiency in the preceding example?

SOLUTION The dc current though the biasing resistors is:

$$I_{\text{bias}} \approx \frac{20 \text{ V}}{215\ \Omega} = 0.093 \text{ A}$$

Next, we need to calculate the dc current through the upper transistor. Here is how to do it: As shown in Fig. 12-18*a*, the saturation current is:

$$I_{C(\text{sat})} = \frac{V_{CEQ}}{R_L} = \frac{10 \text{ V}}{8\ \Omega} = 1.25 \text{ A}$$

The collector current in the conducting transistor is a half-wave signal with a peak of $I_{C(\text{sat})}$. Therefore, it has an average value of:

$$I_{\text{av}} = \frac{I_{C(\text{sat})}}{\pi} = \frac{1.25 \text{ A}}{\pi} = 0.398 \text{ A}$$

The total current drain is:

$$I_{\text{dc}} = 0.093 \text{ A} + 0.398 \text{ A} = 0.491 \text{ A}$$

The dc input power is:

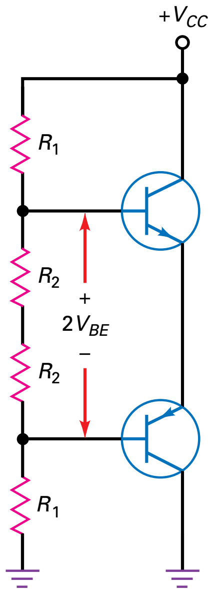
$$P_{\text{dc}} = (20 \text{ V})(0.491 \text{ A}) = 9.82 \text{ W}$$

The efficiency of the stage is:

$$\eta = \frac{p_{\text{out}}}{P_{\text{dc}}} \times 100\% = \frac{6.25 \text{ W}}{9.82 \text{ W}} \times 100\% = 63.6\%$$

PRACTICE PROBLEM 12-9 Repeat Example 12-9 using +30 V for V_{CC}.

Figure 12-20 Voltage-divider bias of class B push-pull amplifier.



GOOD TO KNOW

In actual designs, the compensating diodes are mounted on the case of the power transistors so that, as the transistors heat up so do the diodes. The diodes are usually mounted to the power transistors with a nonconductive adhesive that has good thermal transfer characteristics.

12-6 Biasing Class B/AB Amplifiers

As mentioned earlier, the hardest thing about designing a class B/AB amplifier is setting up a stable *Q* point near cutoff. This section discusses the problem and its solution.

Voltage-Divider Bias

Figure 12-20 shows voltage-divider bias for a class B/AB push-pull circuit. The two transistors have to be complementary; that is, they must have similar V_{BE} curves, maximum ratings, and so forth. For instance, the 2N3904 and 2N3906 are complementary, the first being an *npn* transistor and the second being a *pnp*. They have similar V_{BE} curves, maximum ratings, and so on. Complementary pairs like these are available for almost any class B/AB push-pull design.

To avoid crossover distortion in Fig. 12-20, we set the *Q* point slightly above cutoff, with the correct V_{BE} somewhere between 0.6 and 0.7 V. But here is the major problem: The collector current is very sensitive to changes in V_{BE}. Data sheets indicate that an increase of 60 mV in V_{BE} produces 10 times as much collector current. Because of this, an adjustable resistor is needed to set the correct *Q* point.

But an adjustable resistor does not solve the temperature problem. Even though the *Q* point may be perfect at room temperature, it will change when the temperature changes. As discussed earlier, V_{BE} decreases approximately 2 mV per degree rise. As the temperature increases in Fig. 12-20, the fixed voltage on each emitter diode forces the collector current to increase rapidly. If the temperature increases 30°, the collector current increases by a factor of 10 because the fixed bias is 60 mV too high. Therefore, the *Q* point is very unstable with voltage-divider bias.

The ultimate danger in Fig. 12-20 is **thermal runaway.** When the temperature increases, the collector current increases. As the collector current increases, the junction temperature increases even more, further reducing the correct V_{BE}. This escalating situation means that the collector current may "run away" by rising until excessive power destroys the transistor.

Whether or not thermal runaway takes place depends on the thermal properties of the transistor, how it is cooled, and the type of heat sink used. More often than not, voltage-divider bias like Fig. 12-20 will produce thermal runaway, which destroys the transistors.

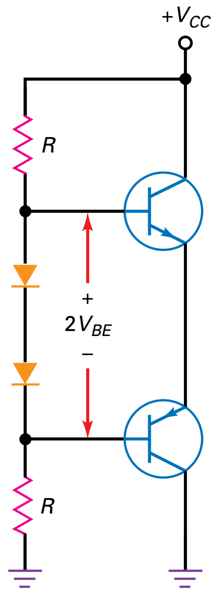
Diode Bias

One way to avoid thermal runaway is with diode bias, shown in Fig. 12-21. The idea is to use **compensating diodes** to produce the bias voltage for the emitter diodes. For this scheme to work, the diode curves must match the V_{BE} curves of the transistors. Then, any increase in temperature reduces the bias voltage developed by the compensating diodes by just the right amount.

For instance, assume that a bias voltage of 0.65 V sets up 2 mA of collector current. If the temperature rises 30°C, the voltage across each compensating diode drops 60 mV. Since the required V_{BE} also decreases by 60 mV, the collector current remains fixed at 2 mA.

For diode bias to be immune to changes in temperature, the diode curves must match the V_{BE} curves over a wide temperature range. This is not easily done with discrete circuits because of the tolerance of components. But diode bias is easy to implement with integrated circuits because the diodes and transistors are on the same chip, which means that they have almost identical curves.

Figure 12-21 Diode bias of class B push-pull amplifier.



With diode bias, the bias current through the compensating diodes of Fig. 12-21 is:

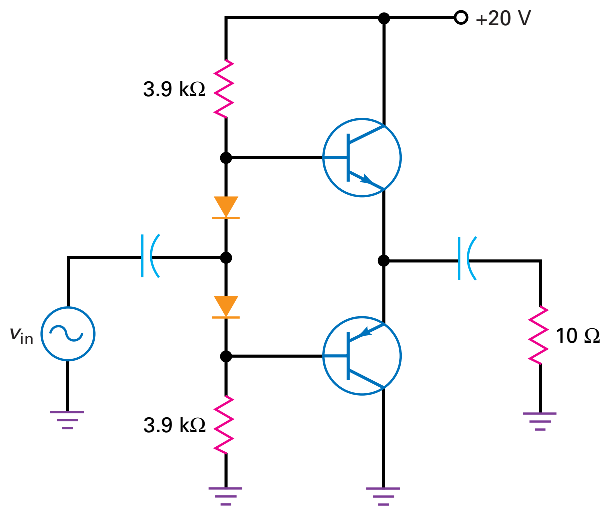
$$I_{\text{bias}} = \frac{V_{CC} - 2V_{BE}}{2R} \quad \text{(12-28)}$$

When the compensating diodes match the V_{BE} curves of the transistors, I_{CQ} has the same value as I_{bias}. (For details, see Sec. 17-7.) As mentioned earlier, I_{CQ} should be between 1 and 5 percent of $I_{C(\text{sat})}$ to avoid crossover distortion.

Example 12-10

What is the quiescent collector current in Fig. 12-22? The maximum efficiency of the amplifier?

Figure 12-22 Example.



SOLUTION The bias current through the compensating diodes is:

$$I_{\text{bias}} = \frac{20\text{ V} - 1.4\text{ V}}{2(3.9\text{ k}\Omega)} = 2.38\text{ mA}$$

This is the value of the quiescent collector current, assuming that the compensating diodes match the emitter diodes.

The collector saturation current is:

$$I_{C(\text{sat})} = \frac{V_{CEQ}}{R_L} = \frac{10\text{ V}}{10\ \Omega} = 1\text{ A}$$

The average value of the half-wave collector current is:

$$I_{\text{av}} = \frac{I_{C(\text{sat})}}{\pi} = \frac{1\text{ A}}{\pi} = 0.318\text{ A}$$

The total current drain is

$$I_{\text{dc}} = 2.38\text{ mA} + 0.318\text{ A} = 0.32\text{ A}$$

The dc input power is:

$$P_{dc} = (20\text{ V})(0.32\text{ A}) = 6.4\text{ W}$$

The maximum ac output power is:

$$p_{out(max)} = \frac{MPP^2}{8R_L} = \frac{(20\text{ V})^2}{8(10\ \Omega)} = 5\text{ W}$$

The efficiency of the stage is:

$$\eta = \frac{p_{out}}{P_{dc}} \times 100\% = \frac{5\text{ W}}{6.4\text{ W}} \times 100\% = 78.1\%$$

PRACTICE PROBLEM 12-10 Repeat Example 12-10 using +30 V for V_{CC}.

12-7 Class B/AB Driver

In the earlier discussion of the class B/AB push-pull emitter follower, the ac signal was capacitively coupled into the bases. This is not the preferred way to drive a class B/AB push-pull amplifier.

CE Driver

The stage that precedes the output stage is called a **driver.** Rather than capacitively couple into the output push-pull stage, we can use the direct-coupled CE driver shown in Fig. 12-23*a*. Transistor Q_1 is a current source that sets up the dc biasing current through the diodes. By adjusting R_2, we can control the dc emitter current through R_4. This means that Q_1 sources the biasing current through the compensating diodes.

When an ac signal drives the base of Q_1, it acts like a swamped amplifier. The amplified and inverted ac signal at the Q_1 collector drives the bases of Q_2 and Q_3. On the positive half cycle, Q_2 conducts and Q_3 cuts off. On the negative half cycle, Q_2 cuts off and Q_3 conducts. Because the output coupling capacitor is an ac short, the ac signal is coupled to the load resistance.

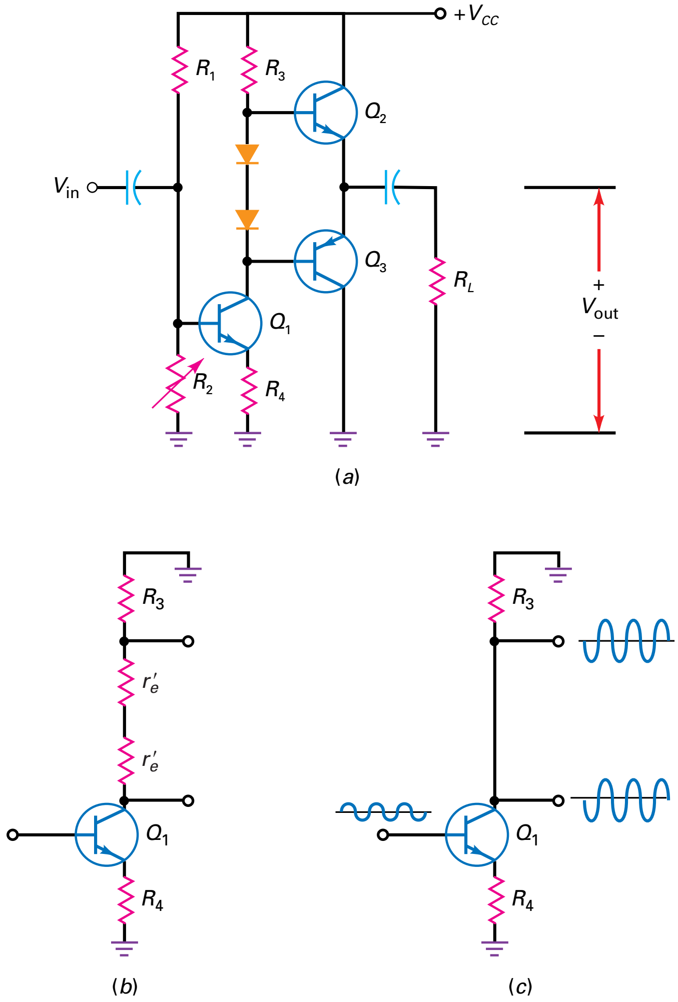
Figure 12-23*b* shows the ac equivalent circuit of the CE driver. The diodes are replaced by their ac emitter resistances. In any practical circuit, r'_e is at least 100 times smaller than R_3. Therefore, the ac equivalent circuit simplifies to Fig. 12-23*c*.

Now, we can see that the driver stage is a swamped amplifier whose amplified and inverted output drives both bases of the output transistors with the same signal. Often, the input impedance of the output transistors is very high, and we can approximate the voltage gain of the driver by:

$$A_V = \frac{R_3}{R_4}$$

In short, the driver stage is a swamped voltage amplifier that produces a large signal for the output push-pull amplifier.

Figure 12-23 (*a*) Direct-coupled CE driver; (*b*) ac equivalent circuit; (*c*) simplified ac equivalent circuit.



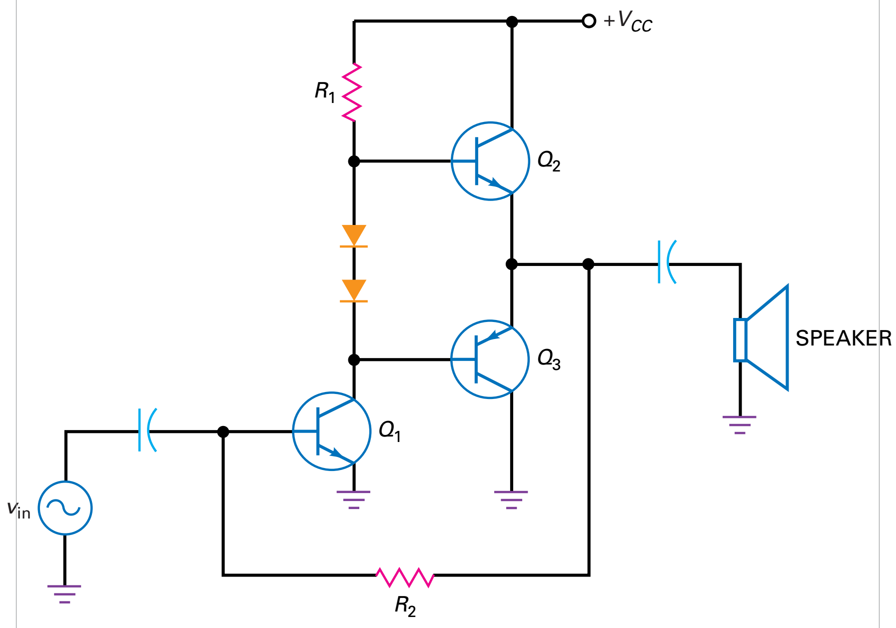
Two-Stage Negative Feedback

Figure 12-24 is another example of using a large-signal CE stage to drive a class B/AB push-pull emitter follower. The input signal is amplified and inverted by the Q_1 driver. The push-pull stage then provides the current gain needed to drive the low-impedance loudspeaker. Notice that the CE driver has its emitter connected to ground. As a result, this driver has more voltage gain than the driver of Fig. 12-23*a*.

The resistance R_2 does two useful things: First, since it is connected to a dc voltage of $+V_{CC}/2$, this resistance provides the dc bias for Q_1. Second, R_2 produces negative feedback for the ac signal. Here's why: A positive-going signal on the base of Q_1 produces a negative-going signal on the Q_1 collector. The output of the emitter follower is therefore negative-going. When fed back through R_2 to the Q_1 base, this returning signal opposes the original input signal. This is negative feedback, which stabilizes the bias and the voltage gain of the overall amplifier.

Integrated circuit (IC) audio power amplifiers are often used in low- to medium-power applications. These amplifiers, such as a LM380 IC, contain class AB biased output transistors and will be discussed in Chap. 18.

Figure 12-24 Two-stage negative feedback to CE driver.



12-8 Class C Operation

With class B, we need to use a push-pull arrangement. That's why almost all class B amplifiers are push-pull amplifiers. With class C, we need to use a resonant circuit for the load. This is why almost all class C amplifiers are tuned amplifiers.

Resonant Frequency

With class C operation, the collector current flows for less than half a cycle. A parallel resonant circuit can filter the pulses of collector current and produce a pure sine wave of output voltage. The main application for class C is with tuned RF amplifiers. The maximum efficiency of a tuned class C amplifier is 100 percent.

Figure 12-25*a* shows a tuned RF amplifier. The ac input voltage drives the base, and an amplified output voltage appears at the collector. The amplified and inverted signal is then capacitively coupled to the load resistance. Because of the parallel resonant circuit, the output voltage is maximum at the resonant frequency, given by:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{12-29}$$

On either side of the resonant frequency f_r, the voltage gain drops off as shown in Fig. 12-25*b*. For this reason, a tuned class C amplifier is always intended to amplify a narrow band of frequencies. This makes it ideal for amplifying radio and television signals because each station or channel is assigned a narrow band of frequencies on both sides of a center frequency.

The class C amplifier is unbiased, as shown in the dc equivalent circuit of Fig. 12-25*c*. The resistance R_S in the collector circuit is the series resistance of the inductor.

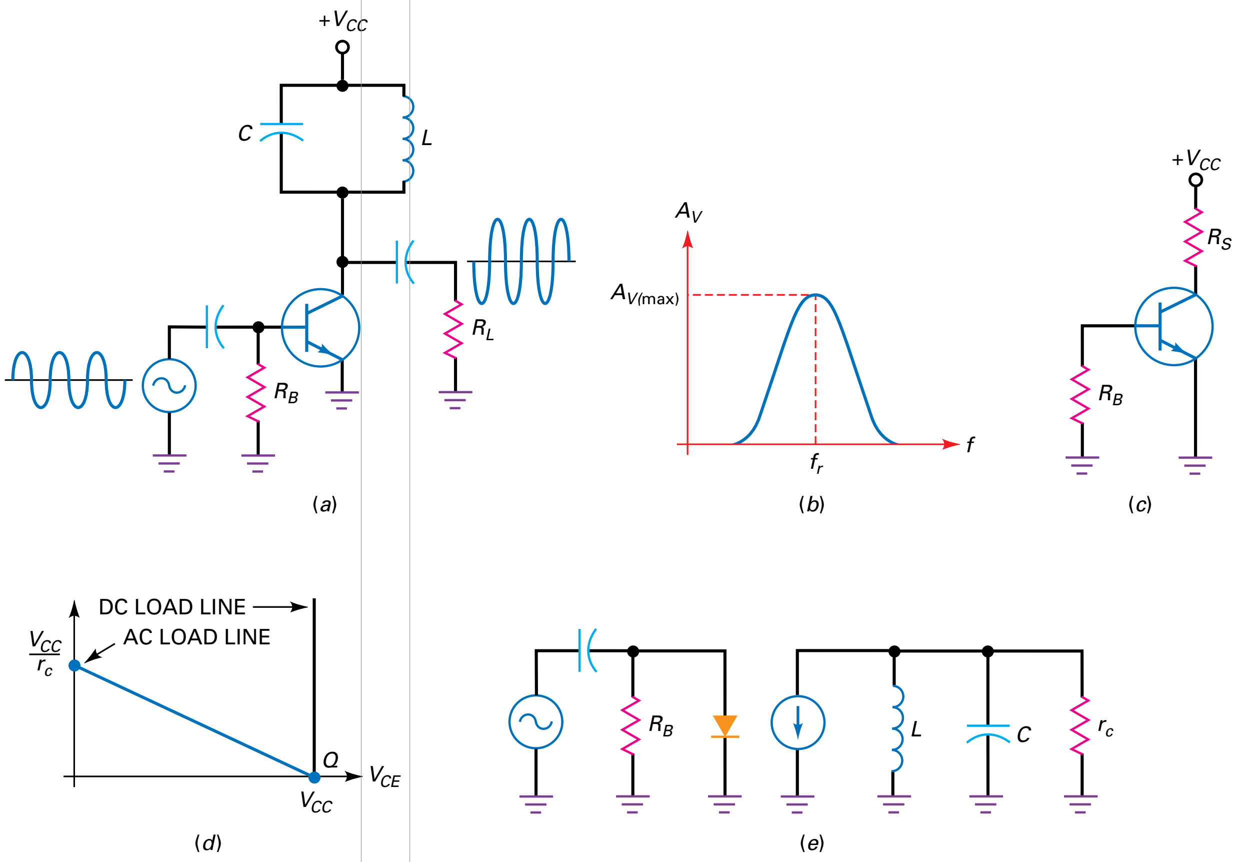
Load Lines

Figure 12-25*d* shows the two load lines. The dc load line is approximately vertical because the winding resistance R_S of an RF inductor is very small. The dc load

GOOD TO KNOW

Most class C amplifiers are designed so that the peak value of input voltage is just sufficient to drive the transistor into saturation.

Figure 12-25 (*a*) Tuned class C amplifier; (*b*) voltage gain versus frequency; (*c*) dc equivalent circuit is unbiased; (*d*) two load lines; (*e*) ac equivalent circuit.



line is not important because the transistor is unbiased. What is important is the ac load line. As indicated, the Q point is at the lower end of the ac load line. When an ac signal is present, the instantaneous operating point moves up the ac load line toward the saturation point. The maximum pulse of collector current is given by the saturation current V_{CC}/r_c.

DC Clamping of Input Signal

Figure 12-25*e* is the ac equivalent circuit. The input signal drives the emitter diode, and the amplified current pulses drive the resonant tank circuit. In a tuned class C amplifier the input capacitor is part of a negative dc clamper. For this reason, the signal appearing across the emitter diode is negatively clamped.

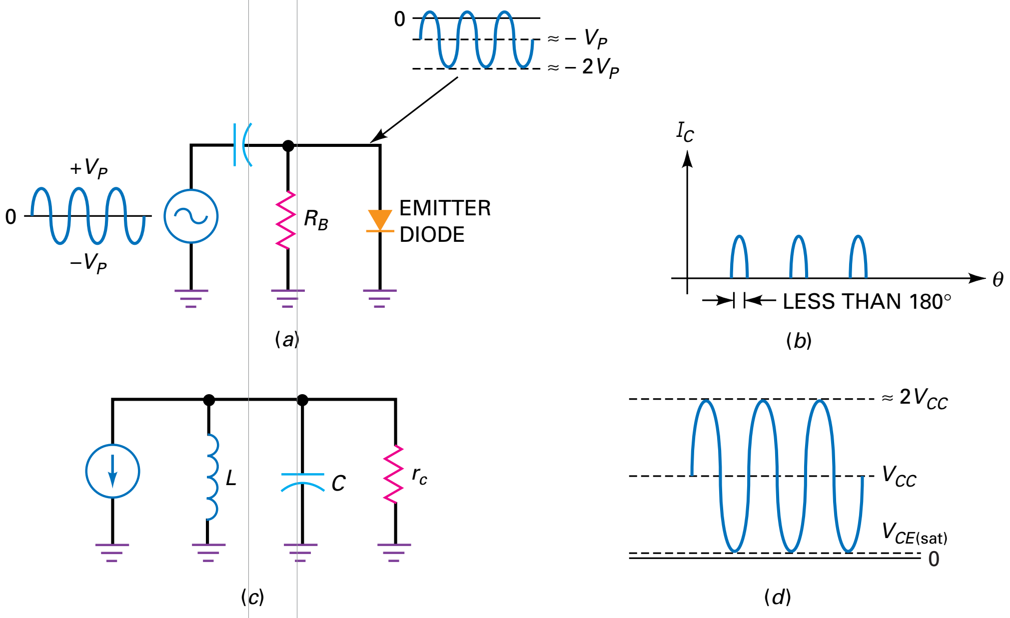
Figure 12-26*a* illustrates the negative clamping. Only the positive peaks of the input signal can turn on the emitter diode. For this reason, the collector current flows in brief pulses like those of Fig. 12-26*b*.

Filtering the Harmonics

Chapter 5 briefly discussed the concept of harmonics. The basic idea is this: A nonsinusoidal waveform like Fig. 12-26*b* is rich in **harmonics,** multiples of the input frequency. In other words, the pulses of Fig. 12-26*b* are equivalent to a group of sine waves with frequencies of f, $2f$, $3f$, . . . , nf.

The resonant tank circuit of Fig. 12-26*c* has a high impedance only at the fundamental frequency f. This produces a large voltage gain at the fundamental frequency. On the other hand, the tank circuit has a very low impedance to the

Figure 12-26 (*a*) Input signal is negatively clamped at base; (*b*) collector current flows in pulses; (*c*) ac collector circuit; (*d*) collector voltage waveform.



higher harmonics, producing very little voltage gain. This is why the voltage across the resonant tank looks almost like the pure sine wave of Fig. 12-26*d*. Since all higher harmonics are filtered, only the fundamental frequency appears across the tank circuit.

Troubleshooting

Since the tuned class C amplifier has a negatively clamped input signal, you can use a high-impedance dc voltmeter to measure the voltage across the emitter diode. If the circuit is working correctly, you should read a negative voltage approximately equal to the peak of the input signal.

The voltmeter test just described is useful when an oscilloscope is not handy. If you have an oscilloscope, however, an even better test is to look across the emitter diode. You should see a negatively clamped waveform when the circuit is working properly.

Example 12-11

Describe the action of Fig. 12-27.

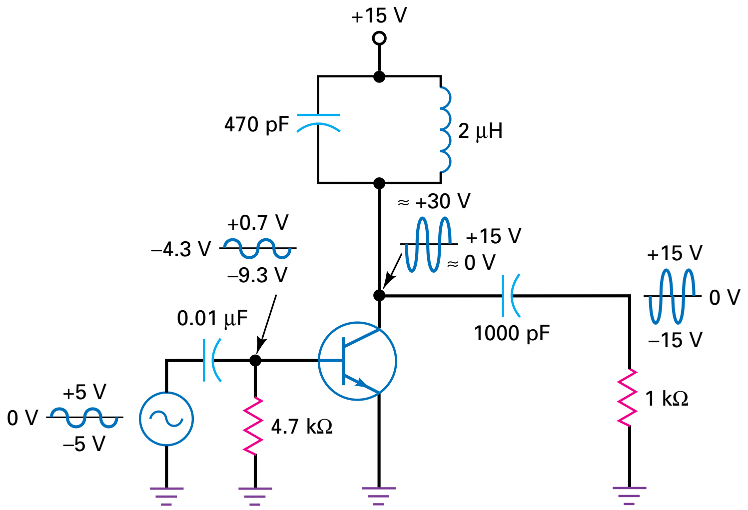
SOLUTION The circuit has a resonant frequency of:

$$f_r = \frac{1}{2\pi\sqrt{(2\ \mu\text{H})(470\ \text{pF})}} = 5.19\ \text{MHz}$$

If the input signal has this frequency, the tuned class C circuit will amplify the input signal.

In Fig. 12-27, the input signal has a peak-to-peak value of 10 V. The signal is negatively clamped at the base of the transistor with a positive peak of

Figure 12-27 Example.



+0.7 V and a negative peak of −9.3 V. The average base voltage is −4.3 V, which can be measured with a high-impedance dc voltmeter.

The collector signal is inverted because of the CE connection. The dc or average voltage of the collector waveform is +15 V, the supply voltage. Therefore, the peak-to-peak collector voltage is 30 V. This voltage is capacitively coupled to the load resistance. The final output voltage has a positive peak of +15 V and a negative peak of −15 V.

PRACTICE PROBLEM 12-11 Using Fig. 12-27, change the 470 pF capacitor to 560 pF and V_{CC} to +12 V. Solve the circuit for f_r and V_{out} peak-to-peak.

12-9 Class C Formulas

A tuned class C amplifier is usually a narrowband amplifier. The input signal in a class C circuit is amplified to get large output power with an efficiency approaching 100 percent.

Bandwidth

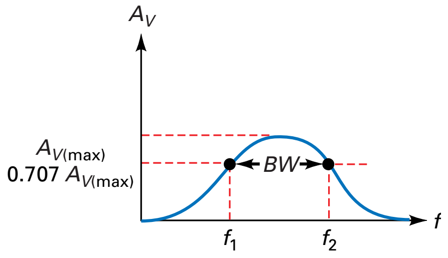
As discussed in basic courses, the **bandwidth (BW)** of a resonant circuit is defined as:

$$BW = f_2 - f_1 \tag{12-30}$$

where f_1 = lower half-power frequency
f_2 = upper half-power frequency

The half-power frequencies are identical to the frequencies at which the voltage gain equals 0.707 times the maximum gain, as shown in Fig. 12-28. The smaller *BW* is, the narrower the bandwidth of the amplifier.

Figure 12-28 Bandwidth.



With Eq. (12-30), it is possible to derive this new relation for bandwidth:

$$BW = \frac{f_r}{Q} \tag{12-31}$$

where Q is the quality factor of the circuit. Equation (12-31) says that the bandwidth is inversely proportional to Q. The higher the Q of the circuit, the smaller the bandwidth.

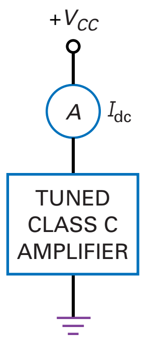
Class C amplifiers almost always have a circuit Q that is greater than 10. This means that the bandwidth is less than 10 percent of the resonant frequency. For this reason, class C amplifiers are narrowband amplifiers. The output of a narrowband amplifier is a large sinusoidal voltage at resonance with a rapid drop-off above and below resonance.

Current Dip at Resonance

When a tank circuit is resonant, the ac load impedance seen by the collector current source is maximum and purely resistive. Therefore, the collector current is minimum at resonance. Above and below resonance, the ac load impedance decreases and the collector current increases.

One way to tune a resonant tank is to look for a decrease in the dc current supplied to the circuit, as shown in Fig. 12-29. The basic idea is to measure the current I_{dc} from the power supply while tuning the circuit (varying either L or C). When the tank is resonant at the input frequency, the ammeter reading will dip to a minimum value. This indicates that the circuit is correctly tuned because the tank has a maximum impedance at this point.

Figure 12-29 Current dip at resonance.

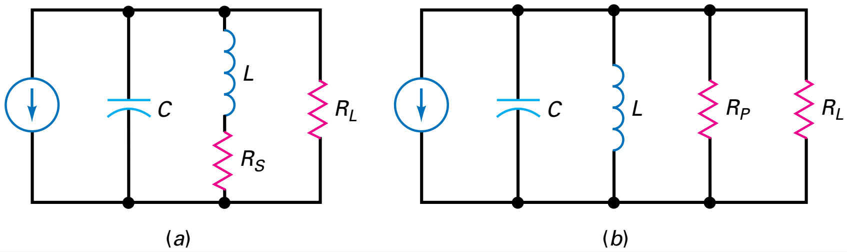


AC Collector Resistance

Any inductor has a series resistance R_S, as indicated in Fig. 12-30*a*. The Q of the inductor is defined as:

$$Q_L = \frac{X_L}{R_S} \tag{12-32}$$

Figure 12-30 (*a*) Series equivalent resistance for inductor; (*b*) parallel equivalent resistance for inductor.



where Q_L = quality factor of coil
X_L = inductive reactance
R_S = coil resistance

Remember that this is the Q of the coil only. The overall circuit has a lower Q because it includes the effect of load resistance as well as coil resistance.

As discussed in basic ac courses, the series resistance of the inductor can be replaced by a parallel resistance R_P, as shown in Fig. 12-30*b*. When Q is greater than 10, this equivalent resistance is given by:

$$R_P = Q_L X_L \tag{12-33}$$

In Fig. 12-30*b*, X_L cancels X_C at resonance, leaving only R_P in parallel with R_L. Therefore, the ac resistance seen by the collector at resonance is:

$$r_c = R_P \parallel R_L \tag{12-34}$$

The *Q of the overall circuit* is given by:

$$Q = \frac{r_c}{X_L} \tag{12-35}$$

This circuit Q is lower than Q_L, the coil Q. In practical class C amplifiers, the Q of the coil is typically 50 or more, and the Q of the circuit is 10 or more. Since the overall Q is 10 or more, the operation is narrowband.

Duty Cycle

The brief turn-on of the emitter diode at each positive peak produces narrow pulses of collector current, as shown in Fig. 12-31*a*. With pulses like these, it is convenient to define the **duty cycle** as:

$$D = \frac{W}{T} \tag{12-36}$$

where D = duty cycle
W = width of pulse
T = period of pulses

For instance, if an oscilloscope displays a pulse width of 0.2 μs and a period of 1.6 μs, the duty cycle is:

$$D = \frac{0.2\ \mu\text{s}}{1.6\ \mu\text{s}} = 0.125$$

The smaller the duty cycle, the narrower the pulses compared to the period. The typical class C amplifier has a small duty cycle. In fact, the efficiency of a class C amplifier increases as the duty cycle decreases.

Conduction Angle

An equivalent way to state the duty cycle is by using the conduction angle ϕ, shown in Fig. 12-31*b*:

$$D = \frac{\phi}{360^\circ} \tag{12-37}$$

Figure 12-31 Duty cycle.

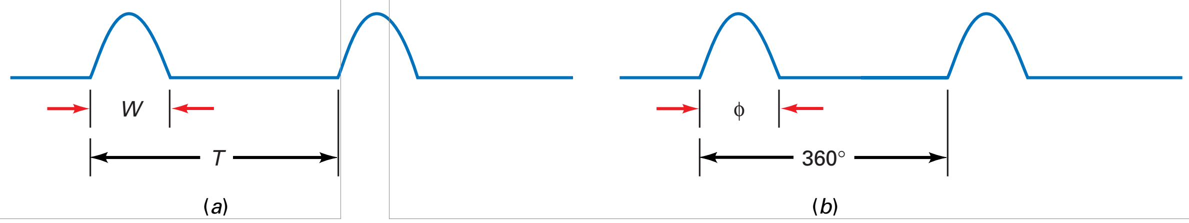
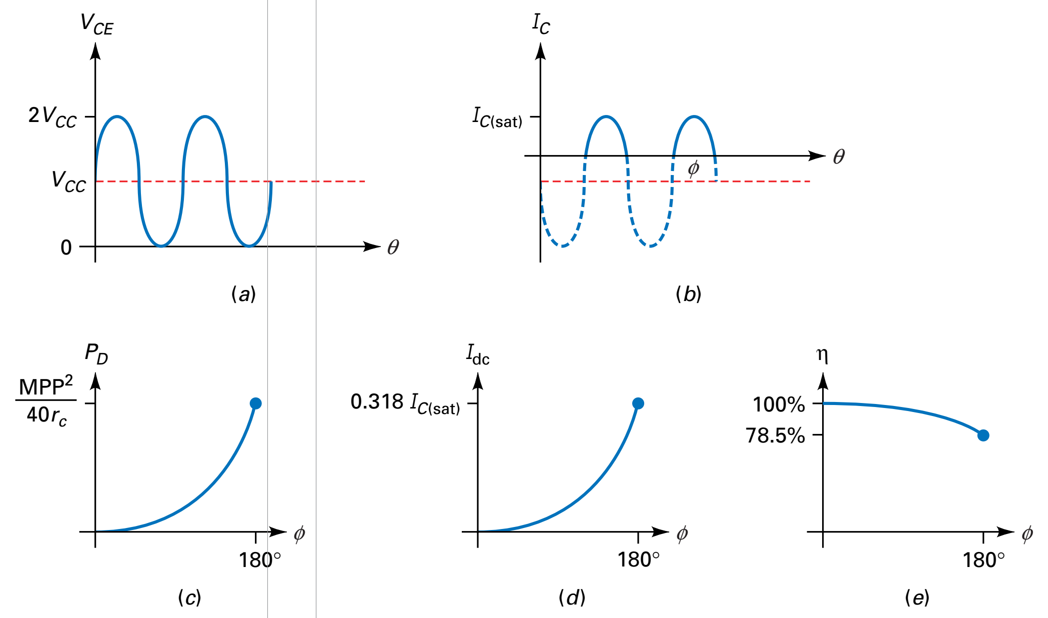


Figure 12-32 (*a*) Maximum output; (*b*) conduction angle; (*c*) transistor power dissipation; (*d*) current drain; (*e*) efficiency.



For instance, if the conduction angle is 18°, the duty cycle is:

$$D = \frac{18°}{360°} = 0.05$$

Transistor Power Dissipation

Figure 12-32*a* shows the ideal collector-emitter voltage in a class C transistor amplifier. In Fig. 12-32*a*, the maximum output is given by:

$$\mathbf{MPP = 2}\boldsymbol{V_{CC}} \qquad \textbf{(12-38)}$$

Since the maximum voltage is approximately $2V_{CC}$, the transistor must have a V_{CEO} rating greater than $2V_{CC}$.

Figure 12-32*b* shows the collector current for a class C amplifier. Typically, the conduction angle ϕ is much less than 180°. Notice that the collector current reaches a maximum value of $I_{C(\text{sat})}$. The transistor must have a peak current rating greater than this. The dotted parts of the cycle represent the off time of the transistor.

The power dissipation of the transistor depends on the conduction angle. As shown in Fig. 12-32*c*, the power dissipation increases with the conduction angle up to 180°. The maximum power dissipation of the transistor can be derived with calculus:

$$\boldsymbol{P_D} = \frac{\mathbf{MPP^2}}{\mathbf{40}\boldsymbol{r_c}} \qquad \textbf{(12-39)}$$

Equation (12-39) represents the worst case. A transistor operating as class C must have a power rating greater than this or it will be destroyed. Under normal drive conditions, the conduction angle will be much less than 180° and the transistor power dissipation will be less than $\text{MPP}^2/40r_c$.

Stage Efficiency

The dc collector current depends on the conduction angle. For a conduction angle of 180° (a half-wave signal), the average or dc collector current is $I_{C(\text{sat})}/\pi$. For smaller conduction angles, the dc collector current is less than this, as shown in

Fig. 12-32*d*. The dc collector current is the only current drain in a class C amplifier because it has no biasing resistors.

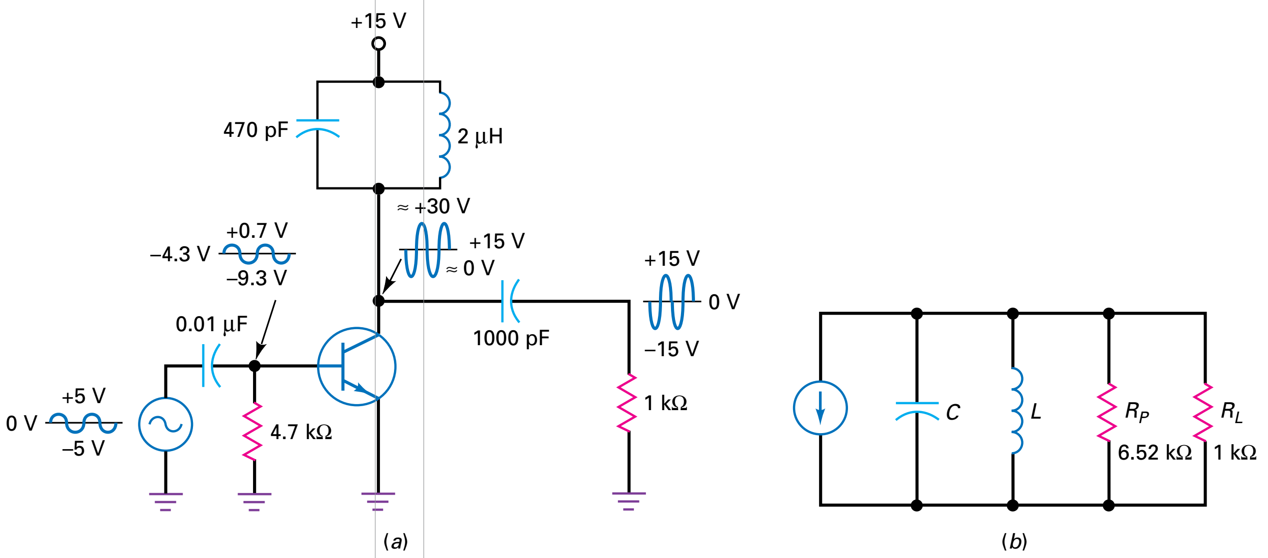
In a class C amplifier, most of the dc input power is converted into ac load power because the transistor and coil losses are small. For this reason, a class C amplifier has high stage efficiency.

Figure 12-32*e* shows how the optimum stage efficiency varies with conduction angle. When the angle is 180°, the stage efficiency is 78.5 percent, the theoretical maximum for a class B amplifier. When the conduction angle decreases, the stage efficiency increases. As indicated, class C has a maximum efficiency of 100 percent, approached at very small conduction angles.

Example 12-12

If Q_L is 100 in Fig. 12-33, what is the bandwidth of the amplifier?

Figure 12-33 Example.



SOLUTION At the resonant frequency (found in Example 12-11):

$$X_L = 2\pi fL = 2\pi(5.19 \text{ MHz})(2\ \mu\text{H}) = 65.2\ \Omega$$

With Eq. (12-33), the equivalent parallel resistance of the coil is:

$$R_P = Q_L X_L = (100)(65.2\ \Omega) = 6.52\ \text{k}\Omega$$

This resistance is in parallel with the load resistance, as shown in Fig. 12-33*b*. Therefore, the ac collector resistance is:

$$r_c = 6.52\ \text{k}\Omega \parallel 1\ \text{k}\Omega = 867\ \Omega$$

With Eq. (12-35), the Q of the overall circuit is:

$$Q = \frac{r_c}{X_L} = \frac{867\ \Omega}{65.2\ \Omega} = 13.3$$

Since the resonant frequency is 5.19 MHz, the bandwidth is:

$$BW = \frac{5.19 \text{ MHz}}{13.3} = 390 \text{ kHz}$$

Example 12-13

In Fig. 12-33*a*, what is the worst-case power dissipation?

SOLUTION The maximum peak-to-peak output is:

$$\text{MPP} = 2V_{CC} = 2(15\text{ V}) = 30\text{ V pp}$$

Equation (12-39) gives us the worst-case power dissipation of the transistor:

$$P_D = \frac{\text{MPP}^2}{40r_c} = \frac{(30\text{ V})^2}{40(867\ \Omega)} = 26\text{ mW}$$

PRACTICE PROBLEM 12-13 In Fig. 12-33, if V_{CC} is +12 V, what is the worst case power dissipation?

12-10 Transistor Power Rating

The temperature at the collector junction places a limit on the allowable power dissipation P_D. Depending on the transistor type, a junction temperature in the range of 150 to 200°C will destroy the transistor. Data sheets specify this maximum junction temperature as $T_{J(\max)}$. For instance, the data sheet of a 2N3904 gives a $T_{J(\max)}$ of 150°C; the data sheet of a 2N3719 specifies a $T_{J(\max)}$ of 200°C.

GOOD TO KNOW

With integrated circuits, a maximum junction temperature cannot be specified because there are so many transistors. Therefore, ICs have a maximum device temperature or case temperature instead. For example, the μA741 op amp IC has a power rating of 500 mW if it is in a metal package, 310 mW if it is in a dual-inline package, and 570 mW if it is in a flatpack.

Ambient Temperature

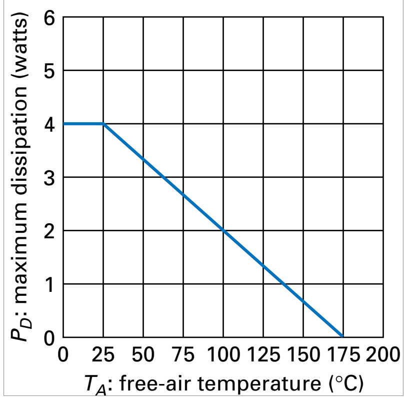
The heat produced at the junction passes through the transistor case (metal or plastic housing) and radiates to the surrounding air. The temperature of this air, known as the *ambient temperature,* is around 25°C, but it can get much higher on hot days. Also, the ambient temperature may be much higher inside a piece of electronic equipment.

Derating Factor

Data sheets often specify the $P_{D(\max)}$ of a transistor at an ambient temperature of 25°C. For instance, the 2N1936 has a $P_{D(\max)}$ of 4 W for an ambient temperature of 25°C. This means that a 2N1936 used in a class A amplifier can have a quiescent power dissipation as high as 4 W. As long as the ambient temperature is 25°C or less, the transistor is within its specified power rating.

What do you do if the ambient temperature is greater than 25°C? You have to derate (reduce) the power rating. Data sheets sometimes include a *derating curve* like the one in Fig. 12-34. As you can see, the power rating decreases when the ambient temperature increases. For instance, at an ambient temperature of 100°C, the power rating is 2 W.

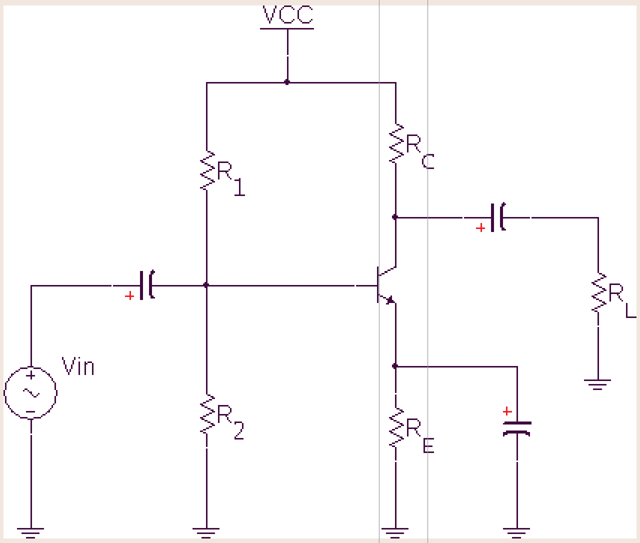
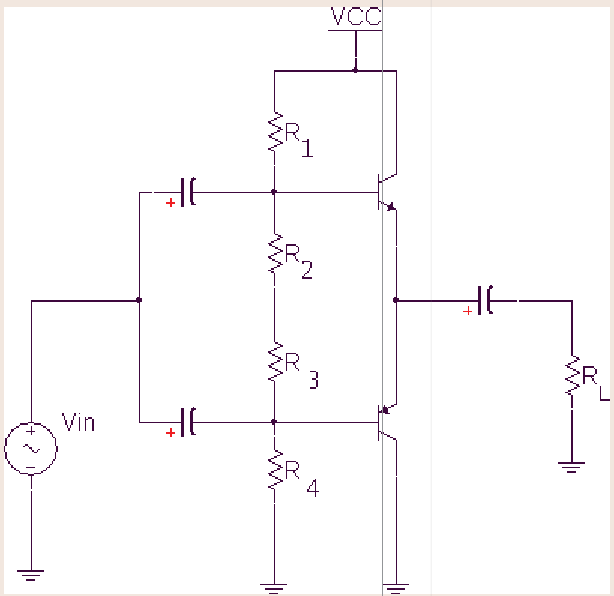
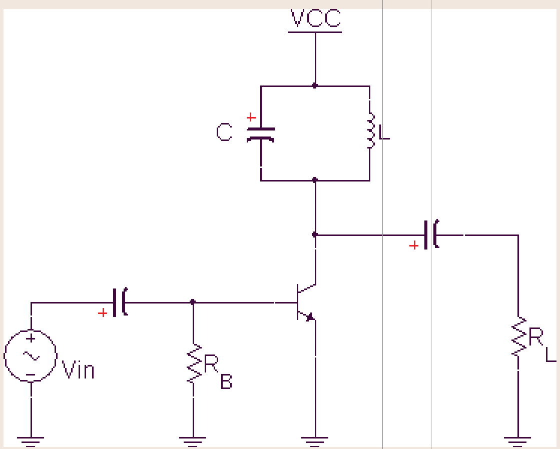
Figure 12-34 Power rating versus ambient temperature.



Some data sheets do not give a derating curve like the one in Fig. 12-34. Instead, they list a derating factor D. For instance, the derating factor of a 2N1936 is 26.7 mW/°C. This means that you have to subtract 26.7 mW for each degree the ambient temperature is above 25°C. In symbols:

$$\Delta P = D(T_A - 25°\text{C}) \tag{12-40}$$

where ΔP = decrease in power rating
D = derating factor
T_A = ambient temperature

Summary Table 12–1	Amplifier Classes	
Circuit	**Characteristics**	**Where used**
	Conducts: 360° Distortion: Small, due to nonlinear distortion Maximum efficiency: 25% MPP < V_{CC} May use transformer coupling to achieve ≈ 50% efficiency	Low-power amplifier where efficiency is not important
	Conducts: ≈ 180° Distortion: Small to moderate, due to crossover distortion Maximum efficiency 78.5% MPP = V_{CC} Uses push-pull effect and complementary output transistors	Output power amp; may use Darlington configurations and diodes for biasing
	Conducts < 180° Distortion: Large Maximum efficiency ≈ 100% Relies on tuned tank circuit MPP = 2 (V_{CC})	Tuned RF power amplifier; final amp stage in communications circuits

As an example, if the ambient temperature rises to 75°C, you have to reduce the power rating by:

$$\Delta P = 26.7 \text{ mW}(75 - 25) = 1.34 \text{ W}$$

Since the power rating is 4 W at 25°C, the new power rating is:

$$P_{D(\max)} = 4 \text{ W} - 1.34 \text{ W} = 2.66 \text{ W}$$

This agrees with the derating curve of Fig. 12-34.

Whether you get the reduced power rating from a derating curve like the one in Fig. 12-34 or from a formula like the one in Eq. (12-40), the important thing to be aware of is the reduction in power rating as the ambient temperature increases. Just because a circuit works well at 25°C doesn't mean it will perform well over a large temperature range. When you design circuits, therefore, you must take the operating temperature range into account by derating all transistors for the highest expected ambient temperature.

Heat Sinks

One way to increase the power rating of a transistor is to get rid of the heat faster. This is why heat sinks are used. If we increase the surface area of the transistor case, we allow the heat to escape more easily into the surrounding air. Look at Fig. 12-35*a*. When this type of heat sink is pushed on to the transistor case, heat radiates more quickly because of the increased surface area of the fins.

Figure 12-35*b* shows the power-tab transistor. The metal tab provides a path out of the transistor for heat. This metal tab can be fastened to the chassis of electronics equipment. Because the chassis is a massive heat sink, heat can easily escape from the transistor to the chassis.

Large power transistors like Fig. 12-35*c* have the collector connected directly to the case to let heat escape as easily as possible. The transistor case is then fastened to the chassis. To prevent the collector from shorting to the chassis ground, a thin insulating washer and a thermal conductive paste are used between the transistor case and the chassis. The important idea here is that heat can leave the transistor more rapidly, which means that the transistor has a higher power rating at the same ambient temperature.

Case Temperature

When heat flows out of a transistor, it passes through the case of the transistor and into the heat sink, which then radiates the heat into the surrounding air. The

Figure 12-35 (*a*) Push-on heat sink; (*b*) power-tab transistor; (*c*) power transistor with collector connected to case.

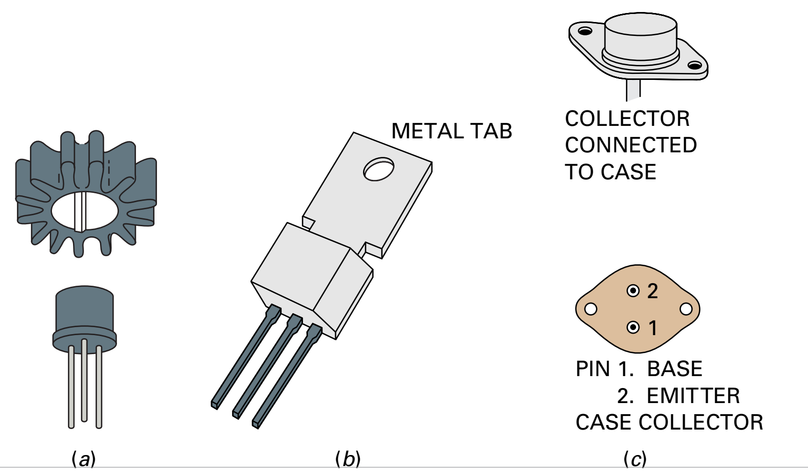
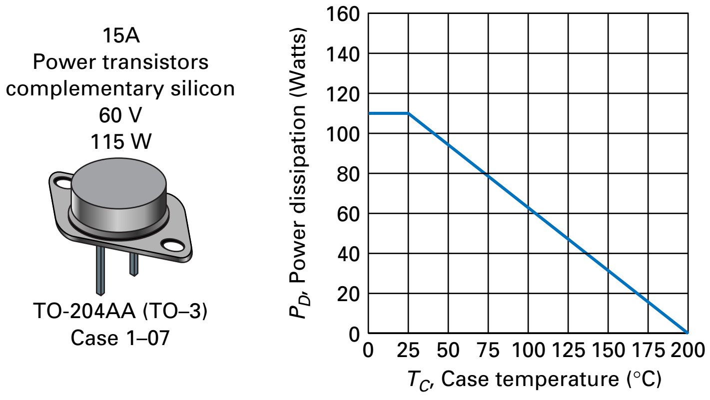


Figure 12-36 2N3055 derating curve. (courtesy of onsemi.com) on semiconductor



temperature of the transistor case T_C will be slightly higher than the temperature of the heat sink T_S which in turn is slightly higher than the ambient temperature T_A.

The data sheets of large power transistors give derating curves for the case temperature rather than the ambient temperature. For instance, Fig. 12-36 shows the derating curve of a 2N3055. The power rating is 115 W at a case temperature of 25°C; then it decreases linearly with temperature until it reaches zero for a case temperature of 200°C.

Sometimes you get a derating factor instead of a derating curve. In this case, you can use the following equation to calculate the reduction in power rating:

$$\Delta P = D(T_C - 25°\text{C}) \tag{12-41}$$

where ΔP = decrease in power rating
D = derating factor
T_C = case temperature

To use the derating curve of a large power transistor, you need to know what the case temperature will be in the worst case. Then you can derate the transistor to arrive at its maximum power rating.

Example 12–14

The circuit of Fig. 12-37 is to operate over an ambient temperature range of 0 to 50°C. What is the maximum power rating of the transistor for the worst-case temperature?

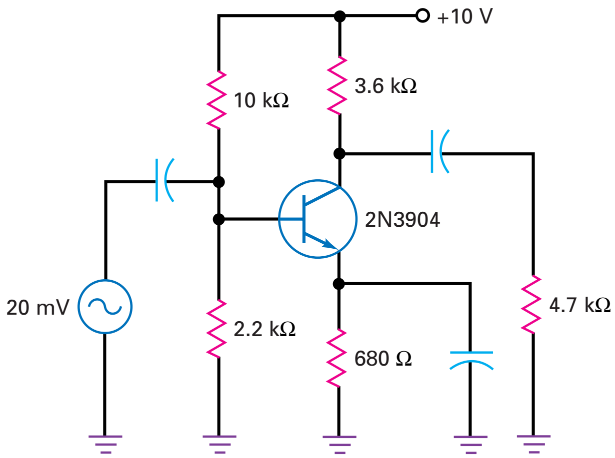
SOLUTION The worst-case temperature is the highest one because you have to derate the power rating given on a data sheet. If you look at the data sheet of a 2N3904 in Fig. 6-15, you will see the maximum power rating is listed as:

$$P_D = 625 \text{ mW at } 25°\text{C ambient}$$

and the derating factor is given as:

$$D = 5 \text{ mW/°C}$$

Figure 12-37 Example.



With Eq. (12-40), we can calculate:

$$\Delta P = (5 \text{ mW})(50 - 25) = 125 \text{ mW}$$

Therefore, the maximum power rating at 50°C is:

$$P_{D(\max)} = 625 \text{ mW} - 125 \text{ mW} = 500 \text{ mW}$$

PRACTICE PROBLEM 12-14 In Example 12-14, what is the transistor's power rating when the ambient temperature is 65°?

Summary

SEC. 12-1 AMPLIFIER TERMS

The classes of operation are A, B, and C. The types of coupling are capacitive, transformer, and direct. Frequency terms include audio, RF, narrowband, and wideband. Some types of audio amplifiers are preamps and power amplifiers.

SEC. 12-2 TWO LOAD LINES

Every amplifier has a dc load line and an ac load line. To get maximum peak-to-peak output, the *Q* point should be in the center of the ac load line.

SEC. 12-3 CLASS A OPERATION

The power gain equals the ac output power divided by the ac input power. The power rating of a transistor must be greater than the quiescent power dissipation. The efficiency of an amplifier stage equals the ac output power divided by the dc input power, times 100 percent. The maximum efficiency of class A with a collector and load resistor is 25%. If the load resistor is the collector resistor or uses a transformer, the maximum efficiency increases to 50 percent.

SEC. 12-4 CLASS B OPERATION

Most class B amplifiers use a push-pull connection of two transistors. While one transistor conducts, the other is cut off, and vice versa. Each transistor amplifies one-half of the ac cycle. The maximum efficiency of class B is 78.5 percent.

SEC. 12-5 CLASS B PUSH-PULL EMITTER FOLLOWER

Class B is more efficient than class A. In a class B push-pull emitter follower, complementary *npn* and *pnp* transistors are used. The *npn* transistor conducts on one half-cycle, and the *pnp* transistor on the other.

SEC. 12-6 BIASING CLASS B/AB AMPLIFIERS

To avoid crossover distortion, the transistors of a class B push-pull emitter follower have a small quiescent current. This is referred to as a class AB. With voltage divider bias, the *Q* point is unstable and may result in thermal runaway. Diode bias is preferred because it can produce a stable *Q* point over a large temperature range.

SEC. 12-7 CLASS B/AB DRIVER

Rather than capacitive couple the signal into the output stage, we can use a direct-coupled driver stage. The collector current out of the driver sets up the quiescent current through the complementary diodes.

SEC. 12-8 CLASS C OPERATION

Most class C amplifiers are tuned RF amplifiers. The input signal is negatively clamped, which produces narrow pulses of collector current. The tank circuit is tuned to the fundamental frequency, so that all higher harmonics are filtered out.

SEC. 12-9 CLASS C FORMULAS

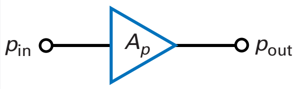
The bandwidth of a class C amplifier is inversely proportional to the Q of the circuit. The ac collector resistance includes the parallel equivalent resistance of the inductor and the load resistance.

SEC. 12-10 TRANSISTOR POWER RATING

The power rating of a transistor decreases as the temperature increases. The data sheet of a transistor either lists a derating factor or shows a graph of the power rating versus temperature. Heat sinks can remove the heat more rapidly, producing a higher power rating.

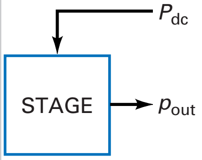
Definitions

(12-12) Power gain:



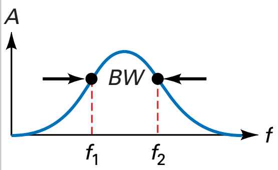
$$A_p = \frac{p_{out}}{p_{in}}$$

(12-18) Efficiency:



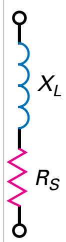
$$\eta = \frac{p_{out}}{P_{dc}} \times 100\%$$

(12-30) Bandwidth:



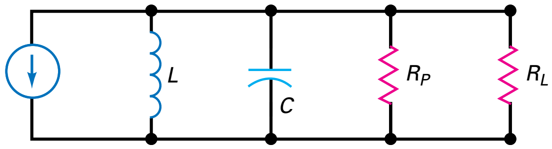
$$BW = f_2 - f_1$$

(12-32) Q of inductor:



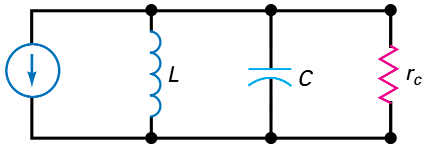
$$Q_L = \frac{X_L}{R_S}$$

(12-33) Equivalent parallel R:



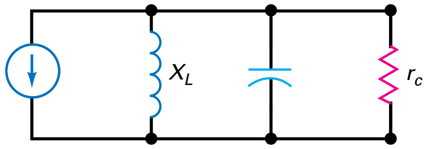
$$R_P = Q_L X_L$$

(12-34) AC collector resistance:



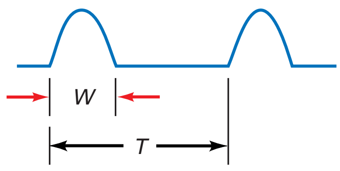
$$r_c = R_P \| R_L$$

(12-35) Q of amplifier:



$$Q = \frac{r_c}{X_L}$$

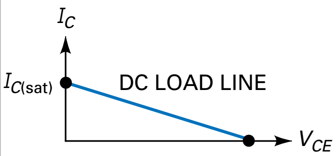
(12-36) Duty cycle:



$$D = \frac{W}{T}$$

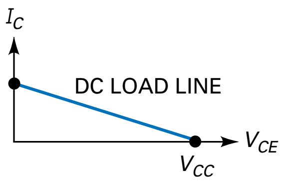
Derivations

(12-1) Saturation current:



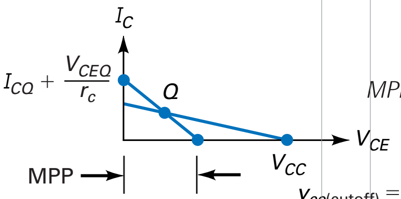
$$I_{C(sat)} = \frac{V_{CC}}{R_C + R_E}$$

(12-2) Cutoff voltage:



$$V_{CE(cutoff)} = V_{CC}$$

(12-7) Limit on output:

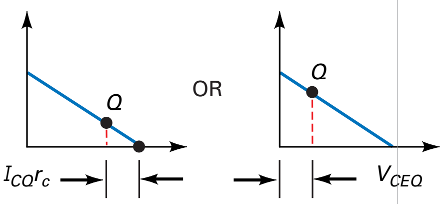


$i_{c(sat)} = I_{CQ} + \frac{V_{CEQ}}{r_c}$

$v_{ce(cutoff)} = V_{CEQ} + I_{CQ}r_c$

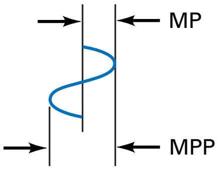
$MPP < V_{CC}$

(12-8) Maximum peak:



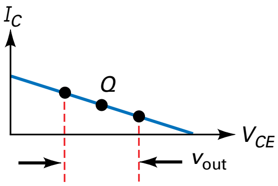
MP $= I_{CQ}r_c$ or MP $= V_{CEQ}$

(12-9) Maximum peak-to-peak output:



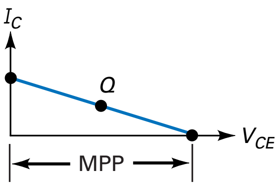
MPP = 2MP

(12-14) Output power:



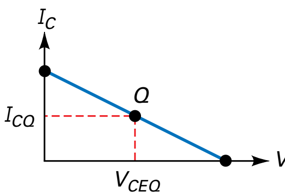
$p_{out} = \frac{v_{out}^2}{8R_L}$

(12-15) Maximum output:



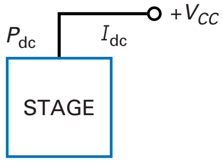
$p_{out(max)} = \frac{\text{MPP}^2}{8R_L}$

(12-16) Transistor power:



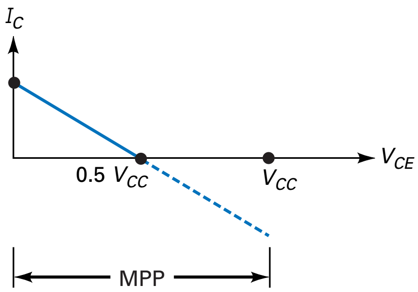
$P_{DQ} = V_{CEQ}I_{CQ}$

(12-17) DC input power:



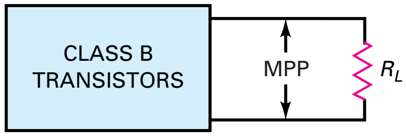
$P_{dc} = V_{CC}I_{dc}$

(12-24) Class B maximum output:



MPP $= V_{CC}$

(12-27) Class B transistor output:

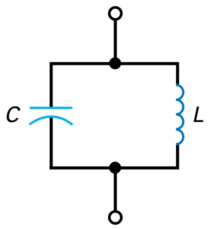


$P_{D(max)} = \frac{\text{MPP}^2}{40R_L}$

(12-28) Class B bias:

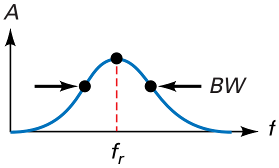
$I_{bias} = \frac{V_{CC} - 2V_{BE}}{2R}$

(12-29) Resonant frequency:



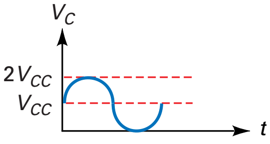
$f_r = \frac{1}{2\pi\sqrt{LC}}$

(12-31) Bandwidth:



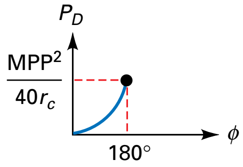
$$BW = \frac{f_r}{Q}$$

(12-38) Maximum output:



$$MPP = 2V_{CC}$$

(12-39) Power dissipation:



$$P_D = \frac{MPP^2}{40r_c}$$

Student Assignments

1. For class B operation, the collector current flows for

a. The whole cycle
b. Half the cycle
c. Less than half a cycle
d. Less than a quarter of a cycle

2. Transformer coupling is an example of

a. Direct coupling
b. AC coupling
c. DC coupling
d. Impedance coupling

3. An audio amplifier operates in the frequency range of

a. 0 to 20 Hz
b. 20 Hz to 2 kHz
c. 20 to 20 kHz
d. Above 20 kHz

4. A tuned RF amplifier is

a. Narrowband
b. Wideband
c. Direct-coupled
d. A dc amplifier

5. The first stage of a preamp is

a. A tuned RF stage
b. Large signal
c. Small signal
d. A dc amplifier

6. For maximum peak-to-peak output voltage, the *Q* point should be

a. Near saturation
b. Near cutoff
c. At the center of the dc load line
d. At the center of the ac load line

7. An amplifier has two load lines because

a. It has ac and dc collector resistances
b. It has two equivalent circuits
c. DC acts one way and ac acts another
d. All of the above

8. When the Q point is at the center of the ac load line, the maximum peak-to-peak output voltage equals

a. V_{CEQ}
b. $2V_{CEQ}$
c. I_{CQ}
d. $2I_{CQ}$

9. Push-pull is almost always used with

a. Class A
b. Class B
c. Class C
d. All of the above

10. One advantage of a class B push-pull amplifier is

a. No quiescent current drain
b. Maximum efficiency of 78.5 percent
c. Greater efficiency than class A
d. All of the above

11. Class C amplifiers are almost always

a. Transformer-coupled between stages
b. Operated at audio frequencies
c. Tuned RF amplifiers
d. Wideband

12. The input signal of a class C amplifier

a. Is negatively clamped at the base
b. Is amplified and inverted
c. Produces brief pulses of collector current
d. All of the above

13. The collector current of a class C amplifier

a. Is an amplified version of the input voltage
b. Has harmonics
c. Is negatively clamped
d. Flows for half a cycle

14. The bandwidth of a class C amplifier decreases when the

a. Resonant frequency increases
b. *Q* increases
c. X_L decreases
d. Load resistance decreases

15. The transistor dissipation in a class C amplifier decreases when the

a. Resonant frequency increases
b. coil *Q* increases
c. Load resistance decreases
d. Capacitance increases

16. The power rating of a transistor can be increased by

a. Raising the temperature
b. Using a heat sink
c. Using a derating curve
d. Operating with no input signal

17. The ac load line is the same as the dc load line when the ac collector resistance equals the

a. DC emitter resistance
b. AC emitter resistance
c. DC collector resistance
d. Supply voltage divided by collector current

18. If $R_C = 100\ \Omega$ and $R_L = 180\ \Omega$, the ac load resistance equals

a. 64 Ω
b. 100 Ω
c. 90 Ω
d. 180 Ω

19. The quiescent collector current is the same as the

a. DC collector current
b. AC collector current
c. Total collector current
d. Voltage-divider current

20. The ac load line usually

a. Equals the dc load line
b. Has less slope than the dc load line
c. Is steeper than the dc oad line
d. Is horizontal

21. For a Q point closer to cutoff than saturation on a CE dc load line, clipping is more likely to occur on the

a. Positive peak of input voltage
b. Negative peak of input voltage
c. Negative peak of output voltage
d. Negative peak of emitter voltage

22. In a class A amplifier, the collector current flows for

a. Less than half the cycle
b. Half the cycle
c. Less than the whole cycle
d. The entire cycle

23. With class A, the output signal should be

a. Unclipped
b. Clipped on positive voltage peak
c. Clipped on negative voltage peak
d. Clipped on negative current peak

24. The instantaneous operating point swings along the

a. AC load line
b. DC load line
c. Both load lines
d. Neither load line

25. The current drain of an amplifier is the

a. Total ac current from the generator
b. Total dc current from the supply
c. Current gain from base to collector
d. Current gain from collector to base

26. The power gain of an amplifier

a. Is the same as the voltage gain
b. Is smaller than the voltage gain
c. Equals output power divided by input power
d. Equals load power

27. Heat sinks reduce the

a. Transistor power
b. Ambient temperature
c. Junction temperature
d. Collector current

28. When the ambient temperature increases, the maximum transistor power rating

a. Decreases
b. Increases
c. Remains the same
d. None of the above

29. If the load power is 300 mW and the dc power is 1.5 W, the efficiency is

a. 0
b. 2 percent
c. 3 percent
d. 20 percent

30. The ac load line of an emitter follower is usually

a. The same as the dc load line
b. Vertical
c. More horizontal than the dc load line
d. Steeper than the dc load line

31. If an emitter follower has V_{CEO} = 6 V, I_{CQ} = 200 mA, and r_e = 10 Ω, the maximum peak-to-peak unclipped output is

a. 2 V
b. 4 V
c. 6 V
d. 8 V

32. The ac resistance of compensating diodes

a. Must be included
b. Is very high
c. Is usually small enough to ignore
d. Compensates for temperature changes

33. If the Q point is at the middle of the dc load line, clipping will first occur on the

a. Left voltage swing
b. Upward current swing
c. Positive half-cycle of input
d. Negative half-cycle of input

34. The maximum efficiency of a class B push-pull amplifier is

a. 25 percent
b. 50 percent
c. 78.5 percent
d. 100 percent

35. A small quiescent current is necessary with a class AB push-pull amplifier to avoid

a. Crossover distortion
b. Destroying the compensating diodes
c. Excessive current drain
d. Loading the driver stage

Problems

SEC. 12-2 TWO LOAD LINES

12-1 What is the dc collector resistance in Fig. 12-38? What is the dc saturation current?

12-2 In Fig. 12-38, what is the ac collector resistance? What is the ac saturation current?

12-3 What is the maximum peak-to-peak output in Fig. 12-38?

12-4 All resistances are doubled in Fig. 12-38. What is the ac collector resistance?

12-5 All resistances are tripled in Fig. 12-38. What is the maximum peak-to-peak output?

Figure 12-38

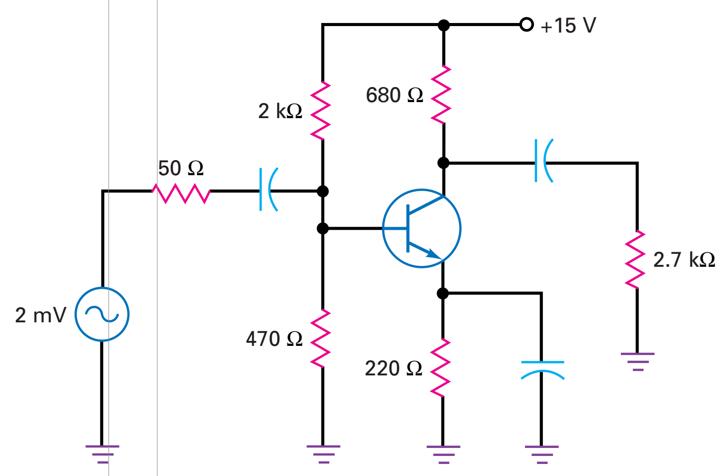
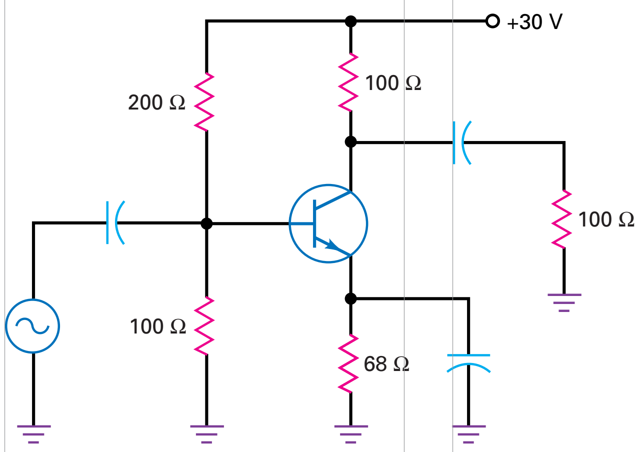


Figure 12-39



12-6 What is the dc collector resistance in Fig. 12-39? What is the dc saturation current?

12-7 In Fig. 12-39, what is the ac collector resistance? What is the ac saturation current?

12-8 What is the maximum peak-to-peak output in Fig. 12-39?

12-9 All resistances are doubled in Fig. 12-39. What is the ac collector resistance?

12-10 All resistances are tripled in Fig. 12-39. What is the maximum peak-to-peak output?

SEC. 12-3 CLASS A OPERATION

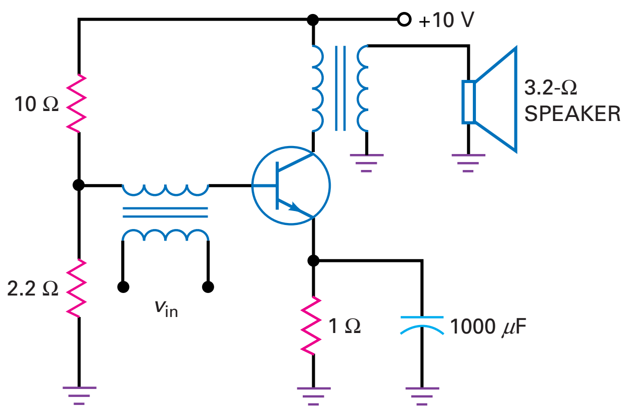
12-11 An amplifier has an input power of 4 mW and output power of 2 W. What is the power gain?

12-12 If an amplifier has a peak-to-peak output voltage of 15 V across a load resistance of 1 kΩ, what is the power gain if the input power is 400 μW?

12-13 What is the current drain in Fig. 12-38?

12-14 What is the dc power supplied to the amplifier of Fig. 12-38?

Figure 12-40



12-15 The input signal of Fig. 12-38 is increased until maximum peak-to-peak output voltage is across the load resistor. What is the efficiency?

12-16 What is the quiescent power dissipation in Fig. 12-38?

12-17 What is the current drain in Fig. 12-39?

12-18 What is the dc power supplied to the amplifier of Fig. 12-39?

12-19 The input signal of Fig. 12-39 is increased until maximum peak-to-peak output voltage is across the load resistor. What is the efficiency?

12-20 What is the quiescent power dissipation in Fig. 12-39?

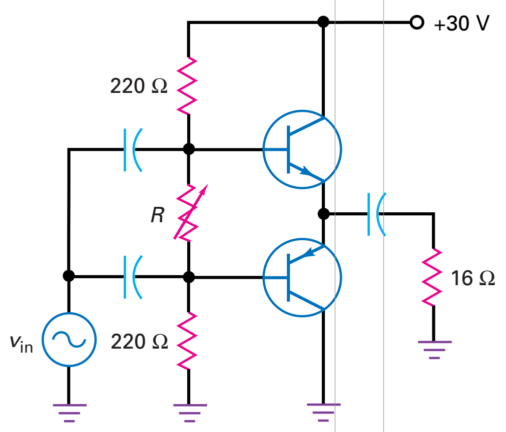
12-21 If V_{BE} = 0.7 V in Fig. 12-40, what is the dc emitter current?

12-22 The speaker of Fig. 12-40 is equivalent to a load resistance of 3.2 Ω. If the voltage across the speaker is 5 V pp, what is the output power? What is the efficiency of the stage?

SEC. 12-6 BIASING CLASS B/AB AMPLIFIERS

12-23 The ac load line of a class B push-pull emitter follower has a cutoff voltage of 12 V. What is the maximum peak-to-peak voltage?

Figure 12-41



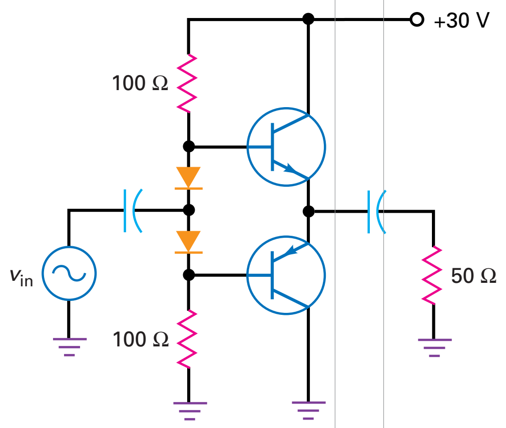
12-24 What is the maximum power dissipation of each transistor of Fig. 12-41?

12-25 What is the maximum output power in Fig. 12-41?

12-26 What is the quiescent collector current in Fig. 12-42?

12-27 In Fig. 12-42, what is the maximum efficiency of the amplifier?

Figure 12-42



12-28 If the biasing resistors of Fig. 12-42 are changed to 1 kΩ, what is the quiescent collector current? The efficiency of the amplifier?

SEC. 12-7 CLASS B/AB DRIVERS

12-29 What is the maximum output power in Fig. 12-43?

12-30 In Fig. 12-43, what is the voltage gain of the first stage if $\beta = 200$?

12-31 If Q_3 and Q_4 have current gains of 200 in Fig. 12-43, what is the voltage gain of the second stage?

12-32 What is the quiescent collector current in Fig. 12-43?

12-33 What is the overall voltage gain for the three-stage amplifier in Fig. 12-43?

SEC. 12-8 CLASS C OPERATION

12-34 If the input voltage equals 5 V rms in Fig. 12-44, what is the peak-to-peak input voltage? If the dc voltage between the base and ground is measured, what will the voltmeter indicate?

12-35 What is the resonant frequency in Fig. 12-44?

12-36 If the inductance is doubled in Fig. 12-44, what is the resonant frequency?

12-37 What is the resonance in Fig. 12-44 if the capacitance is changed to 100 pF?

SEC. 12-9 CLASS C FORMULAS

12-38 If the class C amplifier of Fig. 12-44 has an output power of 11 mW and an input power of 50 μW, what is the power gain?

12-39 What is the output power in Fig. 12-44 if the output voltage is 50 V pp?

12-40 What is the maximum ac output power in Fig. 12-44?

12-41 If the current drain in Fig. 12-44 is 0.5 mA, what is the dc input power?

12-42 What is the efficiency of Fig. 12-44 if the current drain is 0.4 mA and the output voltage is 30 V pp?

Figure 12-43

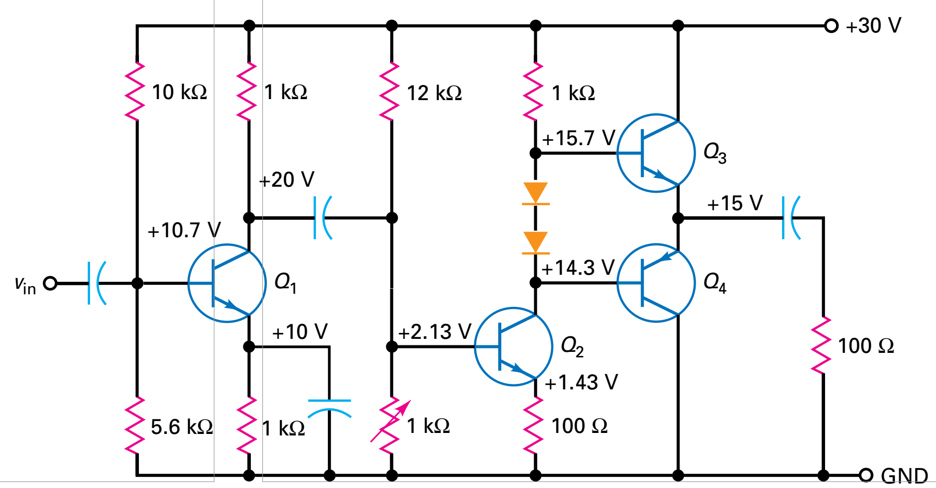
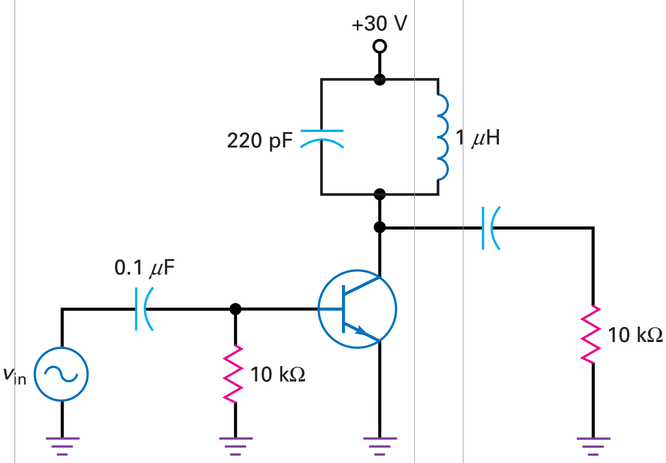


Figure 12-44



12-43 If the Q of the inductor is 125 in Fig. 12-44, what is the bandwidth of the amplifier?

12-44 What is the worst-case transistor power dissipation in Fig. 12-44 ($Q = 125$)?

SEC. 12-10 TRANSISTOR POWER RATING

12-45 A 2N3904 is used in Fig. 12-44. If the circuit has to operate over an ambient temperature range of 0 to 100°C, what is the maximum power rating of the transistor in the worst case?

12-46 A transistor has the derating curve shown in Fig. 12-34. What is the maximum power rating for an ambient temperature of 100°C?

12-47 The data sheet of a 2N3055 lists a power rating of 115 W for a case temperature of 25°C. If the derating factor is 0.657 W/°C, what is $P_{D(max)}$ when the case temperature is 90°C?

Critical Thinking

12-48 The output of an amplifier is a square-wave output even though the input is a sine wave. What is the explanation?

12-49 A power transistor like the one in Fig. 12-36*c* is used in an amplifier. Somebody tells you that since the case is grounded, you can safely touch the case. What do you think about this?

12-50 You are in a bookstore and you read the following in an electronics book: "Some power amplifiers can have an efficiency of 125 percent." Would you buy the book? Explain your answer.

12-51 Normally, the ac load line is more vertical than the dc load line. A couple of classmates say that they are willing to bet that they can draw a circuit whose ac load line is less vertical than the dc load line. Would you take the bet? Explain.

12-52 Draw the dc and ac load lines for Fig. 12-38.

Up-Down Analysis

In Fig. 12-45, P_L is the output power in the load resistor, and P_S is the dc input power from the supply.

12-53 Predict the response of the dependent variables to a slight increase in V_{CC}. Use the table to check your predictions.

12-54 Repeat Prob. 12-53 for a slight increase in R_1.

12-55 Repeat Prob. 12-53 for a slight increase in R_2.

12-56 Repeat Prob. 12-53 for a slight increase in R_E.

12-57 Repeat Prob. 12-53 for a slight increase in R_C.

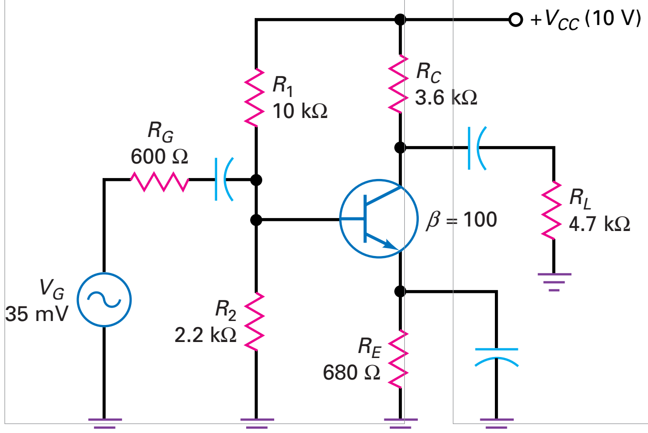
12-58 Repeat Prob. 12-53 for a slight increase in V_G.

12-59 Repeat Prob. 12-53 for a slight increase in R_G.

12-60 Repeat Prob. 12-53 for a slight increase in R_L.

12-61 Repeat Prob. 12-53 for a slight increase in β.

Figure 12-45



(*a*)

UP-Down Analysis

Slight increase	P_L	P_D	P_S	MPP	η
V_{CC}	U	U	U	D	N
R_1	D	U	D	D	D
R_2	U	D	U	D	U
R_E	D	U	D	D	D
R_C	U	D	N	D	U
V_G	U	N	N	N	U
R_G	D	N	N	N	D
R_L	D	N	N	U	D
β	U	N	N	N	U

(*b*)

Job Interview Questions

1. Tell me about the three classes of amplifier operation. Illustrate the classes by drawing collector current waveforms.
2. Draw brief schematics showing the three types of coupling used between amplifier stages.
3. Draw a VDB amplifier. Then, draw its dc load line and ac load line. Assuming that the *Q* point is centered on the ac load lines, what is the ac saturation current? The ac cutoff voltage? The maximum peak-to-peak output?
4. Draw the circuit of a two-stage amplifier and tell me how to calculate the total current drain on the supply.
5. Draw a class C tuned amplifier. Tell me how to calculate the resonant frequency, and tell me what happens to the ac signal at the base. Explain how it is possible that the brief pulses of collector current produce a sine wave of voltage across the resonant tank circuit.
6. What is the most common application of a class C amplifier? Could this type of amplifier be used for an audio application? If not, why not?
7. Explain the purpose of heat sinks. Also, why do we put an insulating washer between the transistor and the heat sink?
8. What is meant by the duty cycle? How is it related to the power supplied by the source?
9. Define *Q*.
10. Which class of amplifier operation is most efficient? Why?
11. You have ordered a replacement transistor and heat sink. In the box with the heat sink is a package containing a white substance. What is it?
12. Comparing a class A amplifier to a class C amplifier, which has the greater fidelity? Why?
13. What type of amplifier is used when only a small range of frequencies is to be amplified?
14. What other types of amplifiers are you familiar with?

Self-Test Answers

1. b
2. b
3. d
4. a
5. c
6. d
7. d
8. b
9. b
10. d
11. c
12. d
13. b
14. b
15. b
16. b
17. c
18. a
19. a
20. c
21. b
22. d
23. a
24. a
25. b
26. c
27. c
28. a
29. d
30. d
31. b
32. c
33. d
34. c
35. a

Practice Problem Answers

12-1 $I_{CQ} = 100$ mA; $V_{CEQ} = 15$ V

12-2 $i_{c(sat)} = 350$ mA; $V_{CE(cutoff)} = 21$ V; MPP = 12 V

12-3 $Ap = 1{,}122$

12-5 $R = 200\ \Omega$

12-6 $I_{CQ} = 331$ mA; $V_{CEQ} = 6.7$ V; $r_e = 8\ \Omega$

12-7 MPP = 5.3 V

12-8 $P_{D(max)} = 2.8$ W; $P_{out(max)} = 14$ W

12-9 Efficiency = 63%

12-10 Efficiency = 78%

12-11 $f_r = 4.76$ MHz; $V_{out} = 24$ V pp

12-13 $P_D = 16.6$ mW

12-14 $P_{D(max)} = 425$ mW