12 Power Amplifiers

CHAPTER OBJECTIVES

- The differences between classes A, AB, and C amplifiers
- What causes amplifier distortion
- Efficiency of various classes of amplifiers
- Power calculations for various class amplifiers

12.1 INTRODUCTION—DEFINITIONS AND AMPLIFIER TYPES

An amplifier receives a signal from some pickup transducer or other input source and provides a larger version of the signal to some output device or to another amplifier stage. An input transducer signal is generally small (a few millivolts from a cassette or CD input, or a few microvolts from an antenna) and needs to be amplified sufficiently to operate an output device (speaker or other power-handling device). In small-signal amplifiers, the main factors are usually amplification linearity and magnitude of gain. Since signal voltage and current are small in a small-signal amplifier, the amount of power-handling capacity and power efficiency are of little concern. A voltage amplifier provides voltage amplification primarily to increase the voltage of the input signal. Large-signal or power amplifiers, on the other hand, primarily provide sufficient power to an output load to drive a speaker or other power device, typically a few watts to tens of watts. In Chapter 12, we concentrate on amplifier circuits used to handle large-voltage signals at moderate to high current levels. The main features of a large-signal amplifier are the circuit's power efficiency, the maximum amount of power that the circuit is capable of handling, and the impedance matching to the output device.

One method used to categorize amplifiers is by class. Basically, amplifier classes represent the amount the output signal varies over one cycle of operation for a full cycle of input signal. A brief description of amplifier classes is provided next.

Class A: The output signal varies for a full 360° of the input signal. Figure12.1a shows that this requires the *Q*-point to be biased at a level so that at least half the signal swing of the output may vary up and down without going to a high enough voltage to be limited by the supply voltage level or too low to approach the lower supply level, or 0 V in this description.

Class B: A class B circuit provides an output signal varying over one-half the input signal cycle, or for 180° of signal, as shown in Fig. 12.1b. The dc bias point for class B is at 0 V, with the output then varying from this bias point for a half-cycle. Obviously, the

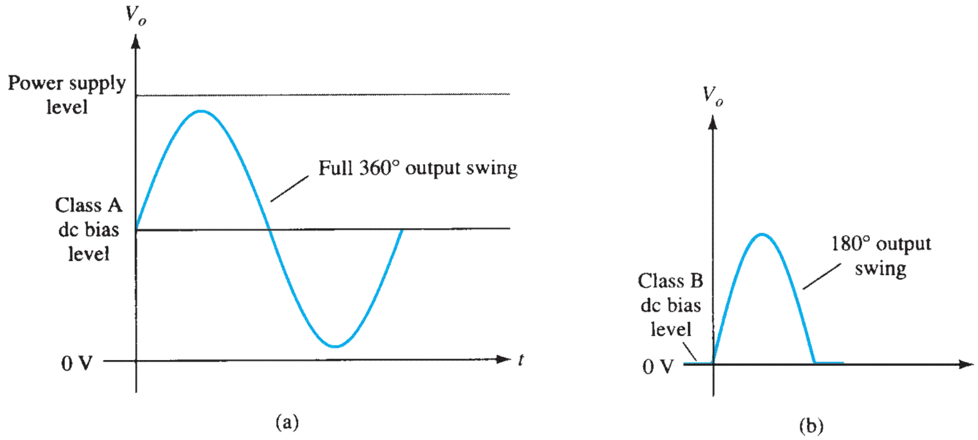

FIG. 12.1
Amplifier operating classes.

output is not a faithful reproduction of the input if only one half-cycle is present. Two class B operations—one to provide output on the positive-output half-cycle and another to provide operation on the negative-output half-cycle—are necessary. The combined half-cycles then provide an output for a full 360° of operation. This type of connection is referred to as *push–pull operation*, which is discussed later in this chapter. Note that class B operation by itself creates a very distorted output signal since reproduction of the input takes place for only 180° of the output signal swing.

Class AB: An amplifier may be biased at a dc level above the zero-base-current level of class B and above one-half the supply voltage level of class A; this bias condition is class AB. Class AB operation still requires a push–pull connection to achieve a full output cycle, but the dc bias level is usually closer to the zero-base-current level for better power efficiency, as described shortly. For class AB operation, the output signal swing occurs between 180° and 360° and is neither class A nor class B operation.

Class C: The output of a class C amplifier is biased for operation at less than 180° of the cycle and will operate only with a tuned (resonant) circuit, which provides a full cycle of operation for the tuned or resonant frequency. This operating class is therefore used in special areas of tuned circuits, such as radio or communications.

Class D: This operating class is a form of amplifier operation using pulse (digital) signals, which are on for a short interval and off for a longer interval. Using digital techniques makes it possible to obtain a signal that varies over the full cycle (using sample-and-hold circuitry) to recreate the output from many pieces of input signal. The major advantage of class D operation is that the amplifier is "on" (using power) only for short intervals and the overall efficiency can practically be very high, as described next.

Amplifier Efficiency

The power efficiency of an amplifier, defined as the ratio of power output to power input, improves (gets higher) going from class A to class D. In general terms, we see that a class A amplifier, with dc bias at one-half the supply voltage level, uses a good amount of power to maintain bias, even with no input signal applied. This results in very poor efficiency, especially with small input signals, when very little ac power is delivered to the load. In fact, the maximum efficiency of a class A circuit, occurring for the largest output voltage and current swing, is only 25% with a direct or series-fed load connection and 50% with a transformer connection to the load. Class B operation, with no dc bias power for no input signal, can be shown to provide a maximum efficiency that reaches 78.5%. Class D operation can achieve power efficiency over 90% and provides the most efficient operation of all the operating classes. Since class AB falls between class A and class B in bias, it also falls between their efficiency ratings—between 25% (or 50%) and 78.5%. Table 12.1 summarizes the operation of the various amplifier classes. This table provides a relative comparison of the output cycle operation and power efficiency for the various class types. In class B operation, a push–pull connection is obtained using either a transformer coupling

TABLE 12.1
Comparison of Amplifier Classes

	Class				
	A	AB	B	C[a]	D
Operating cycle	360°	180° to 360°	180°	Less than 180°	Pulse operation
Power efficiency	25% to 50%	Between 25% (50%) and 78.5%	78.5%		Typically over 90%

[a]*Class C is usually not used for delivering large amounts of power, and thus the efficiency is not given here.*

or by using complementary (or quasi-complementary) operation with *npn* and *pnp* transistors to provide operation on opposite-polarity cycles. Although transformer operation can provide opposite-cycle signals, the transformer itself is quite large in many applications. A transformerless circuit using complementary transistors provides the same operation in a much smaller package. Circuits and examples are provided later in this chapter.

12.2 SERIES-FED CLASS A AMPLIFIER

The simple fixed-bias circuit connection shown in Fig. 12.2 can be used to discuss the main features of a class A series-fed amplifier. The only differences between this circuit and the small-signal version considered previously is that the signals handled by the large-signal circuit are in the range of volts, and the transistor used is a power transistor that is capable of operating in the range of a few to tens of watts. As will be shown in this section, this circuit is not the best to use as a large-signal amplifier because of its poor power efficiency. The beta of a power transistor is generally less than 100, the overall amplifier circuit using power transistors that are capable of handling large power or current while not providing much voltage gain.

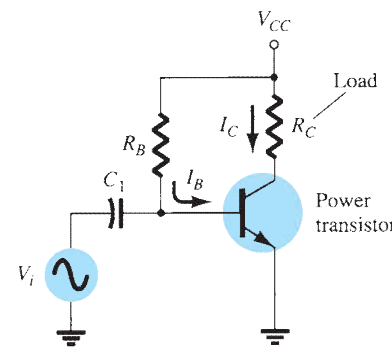

FIG. 12.2
Series-fed class A large-signal amplifier.

DC Bias Operation

The dc bias set by V_{CC} and R_B fixes the dc base-bias current at

$$I_B = \frac{V_{CC} - 0.7\text{ V}}{R_B} \tag{12.1}$$

with the collector current then being

$$I_C = \beta I_B \tag{12.2}$$

with the collector–emitter voltage then

$$V_{CE} = V_{CC} - I_C R_C \tag{12.3}$$

To appreciate the importance of the dc bias on the operation of the power amplifier, consider the collector characteristic shown in Fig. 12.3. A dc load line is drawn using the

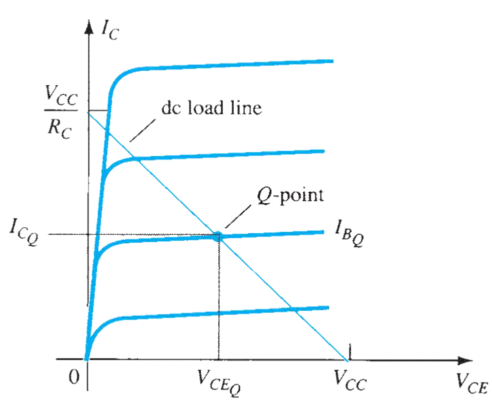

FIG. 12.3
Transistor characteristic showing load line and Q-point.

values of V_{CC} and R_C. The intersection of the dc bias value of I_B with the dc load line then determines the operating point (Q-point) for the circuit. The quiescent-point values are those calculated using Eqs. (12.1) through (12.3). If the dc bias collector current is set at one-half the possible signal swing (between 0 and V_{CC}/R_C), the largest collector current swing will be possible. Additionally, if the quiescent collector–emitter voltage is set at one-half the supply voltage, the largest voltage swing will be possible. With the Q-point set at this optimum bias point, the power considerations for the circuit of Fig. 12.2 are determined as described next.

AC Operation

When an input ac signal is applied to the amplifier of Fig. 12.2, the output will vary from its dc bias operating voltage and current. A small input signal, as shown in Fig. 12.4, will cause the base current to vary above and below the dc bias point, which will then cause the collector current (output) to vary from the dc bias point set as well as the collector–emitter voltage to vary around its dc bias value. As the input signal is made larger, the output will vary further around the established dc bias point until either the current or the voltage reaches a limiting condition. For the current this limiting condition is either zero current at the low end or V_{CC}/R_C at the high end of its swing. For the collector–emitter voltage, the limit is either 0 V or the supply voltage, V_{CC}.

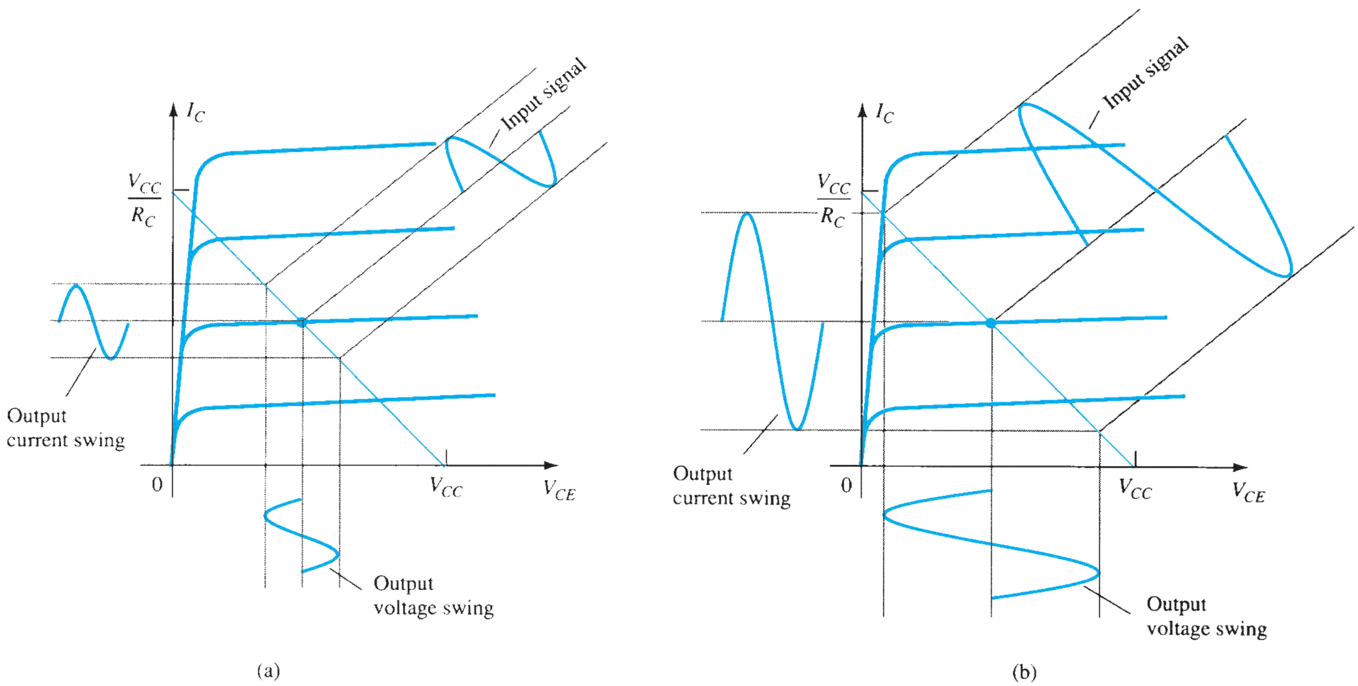

FIG. 12.4
Amplifier input and output signal variation.

Power Considerations

The power into an amplifier is provided by the supply voltage. With no input signal, the dc current drawn is the collector bias current I_{C_Q}. The power then drawn from the supply is

$$P_i(\text{dc}) = V_{CC}I_{C_Q} \qquad \textbf{(12.4)}$$

Even with an ac signal applied, the average current drawn from the supply remains equal to the quiescent current I_{C_Q}, so that Eq. (12.4) represents the input power supplied to the class A series-fed amplifier.

Output Power The output voltage and current varying around the bias point provide ac power to the load. This ac power is delivered to the load R_C in the circuit of Fig. 12.2. The ac signal V_i causes the base current to vary around the dc bias current and the collector current around its quiescent level I_{C_Q}. As shown in Fig. 12.4, the ac input signal results in ac current and ac voltage signals. The larger the input signal, the larger is the output swing, up to the maximum set by the circuit. The ac power delivered to the load (R_C) can be expressed in a number of ways.

Using RMS signals. The ac power delivered to the load (R_C) may be expressed using

$$P_o(\text{ac}) = V_{CE}(\text{rms})I_C(\text{rms}) \tag{12.5}$$

$$P_o(\text{ac}) = I_C^2(\text{rms})R_C \tag{12.6}$$

$$P_o(\text{ac}) = \frac{V_C^2(\text{rms})}{R_C} \tag{12.7}$$

Efficiency

The efficiency of an amplifier represents the amount of ac power delivered (transferred) from the dc source. The efficiency of the amplifier is calculated using

$$\%\,\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% \tag{12.8}$$

Maximum Efficiency For the class A series-fed amplifier, the maximum efficiency can be determined using the maximum voltage and current swings. For the voltage swing it is

$$\text{maximum } V_{CE}(\text{p-p}) = V_{CC}$$

For the current swing it is

$$\text{maximum } I_C(\text{p-p}) = \frac{V_{CC}}{R_C}$$

Using the maximum voltage swing in Eq. (12.7) yields

$$\text{maximum } P_o(\text{ac}) = \frac{V_{CC}(V_{CC}/R_C)}{8} = \frac{V_{CC}^2}{8R_C}$$

The maximum power input can be calculated using the dc bias current set to one-half the maximum value:

$$\text{maximum } P_i(\text{dc}) = V_{CC}(\text{maximum } I_C) = V_{CC}\frac{V_{CC}/R_C}{2} = \frac{V_{CC}^2}{2R_C}$$

We can then use Eq. (12.8) to calculate the maximum efficiency:

$$\text{maximum } \%\,\eta = \frac{\text{maximum } P_o(\text{ac})}{\text{maximum } P_i(\text{dc})} \times 100\% = \frac{V_{CC}^2/8R_C}{V_{CC}^2/2R_C} \times 100\% = 25\%$$

The maximum efficiency of a class A series-fed amplifier is thus seen to be 25%. Since this maximum efficiency will occur only for ideal conditions of both voltage swing and current swing, most series-fed circuits will provide efficiencies of much less than 25%.

EXAMPLE 12.1 Calculate the input power, output power, and efficiency of the amplifier circuit in Fig. 12.5 for an input voltage that results in a base current of 10 mA peak.

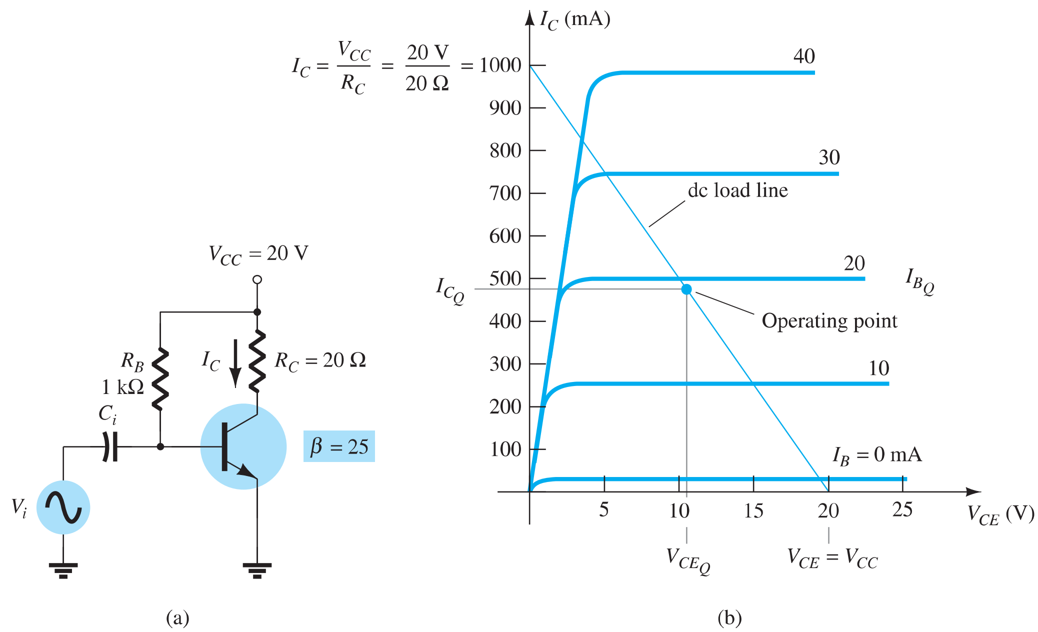

FIG. 12.5
Operation of a series-fed circuit for Example 12.1.

Solution: Using Eqs. (12.1) through (12.3), we can determine the *Q*-point to be

$$I_{B_Q} = \frac{V_{CC} - 0.7\ \text{V}}{R_B} = \frac{20\ \text{V} - 0.7\ \text{V}}{1\ \text{k}\Omega} = 19.3\ \text{mA}$$

$$I_{C_Q} = \beta I_B = 25(19.3\ \text{mA}) = 482.5\ \text{mA} \cong 0.48\ \text{A}$$

$$V_{CE_Q} = V_{CC} - I_C R_C = 20\ \text{V} - (0.48\ \Omega)(20\ \Omega) = 10.4\ \text{V}$$

This bias point is marked on the transistor collector characteristic of Fig. 12.5b. The ac variation of the output signal can be obtained graphically using the dc load line drawn on Fig. 12.5b by connecting $V_{CE} = V_{CC} = 20$ V with $I_C = V_{CC}/R_C = 1000$ mA $= 1$ A, as shown. When the input ac base current increases from its dc bias level, the collector current rises by

$$I_C(\text{p}) = \beta I_B(\text{p}) = 25(10\ \text{mA peak}) = 250\ \text{mA peak}$$

Using Eq. (12.6) yields

$$P_o(\text{ac}) = I_C^2(rms)R_C = \frac{I_C^2(\text{p})}{2}R_C = \frac{(250 \times 10^{-3}\ \text{A})^2}{2}(20\ \Omega) = \mathbf{0.625\ W}$$

Using Eq. (12.4) results in

$$P_i(\text{dc}) = V_{CC}I_{C_Q} = (20\ \text{V})(0.48\ \text{A}) = \mathbf{9.6\ W}$$

The amplifier's power efficiency can then be calculated using Eq. (12.8):

$$\%\ \eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% = \frac{0.625\ \text{W}}{9.6\ \text{W}} \times 100\% = \mathbf{6.5\%}$$

12.3 TRANSFORMER-COUPLED CLASS A AMPLIFIER

A form of class A amplifier having maximum efficiency of 50% uses a transformer to couple the output signal to the load as shown in Fig. 12.6. This is a simple circuit form to use in presenting a few basic concepts. More practical circuit versions are covered later.

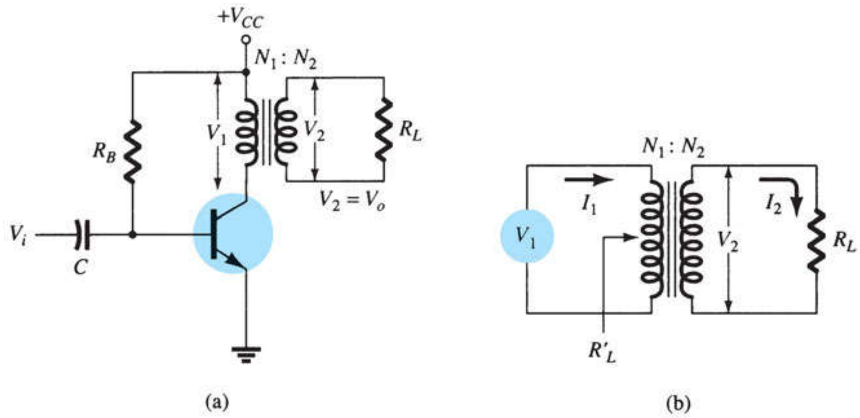

FIG. 12.6
Transformer-coupled audio power amplifier.

Since the circuit uses a transformer to step voltage or current, a review of voltage and current step-up and step-down is presented next.

Transformer Action

A transformer can increase or decrease voltage or current levels according to the turns ratio, as explained below. In addition, the impedance connected to one side of a transformer can be made to appear either larger or smaller (step up or step down) at the other side of the transformer, depending on the square of the transformer winding turns ratio. The following discussion assumes ideal (100%) power transfer from primary to secondary, that is, no power losses are considered.

Voltage Transformation As shown in Fig. 12.7a, the transformer can step up or step down a voltage applied to one side directly as the ratio of the turns (or number of windings) on each side. The voltage transformation is given by

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \tag{12.9}$$

Equation (12.9) shows that if the number of turns of wire on the secondary side is larger than the number on the primary, the voltage at the secondary side is larger than the voltage at the primary side.

Current Transformation The current in the secondary winding is inversely proportional to the number of turns in the windings. The current transformation is given by

$$\frac{I_2}{I_1} = \frac{N_1}{N_2} \tag{12.10}$$

This relationship is shown in Fig. 12.7b. If the number of turns of wire on the secondary is greater than that on the primary, the secondary current will be less than the current in the primary.

Impedance Transformation Since the voltage and current can be changed by a transformer, an impedance "seen" from either side (primary or secondary) can also be changed. As shown in Fig. 12.7c, an impedance R_L is connected across the transformer secondary. This impedance is changed by the transformer when viewed at the primary side (R'_L). This can be shown as follows:

$$\frac{R_L}{R'_L} = \frac{R_2}{R_1} = \frac{V_2/I_2}{V_1/I_1} = \frac{V_2\,I_1}{I_2\,V_1} = \frac{V_2 I_1}{V_1 I_2} = \frac{N_2 N_2}{N_1 N_1} = \left(\frac{N_2}{N_1}\right)^2$$

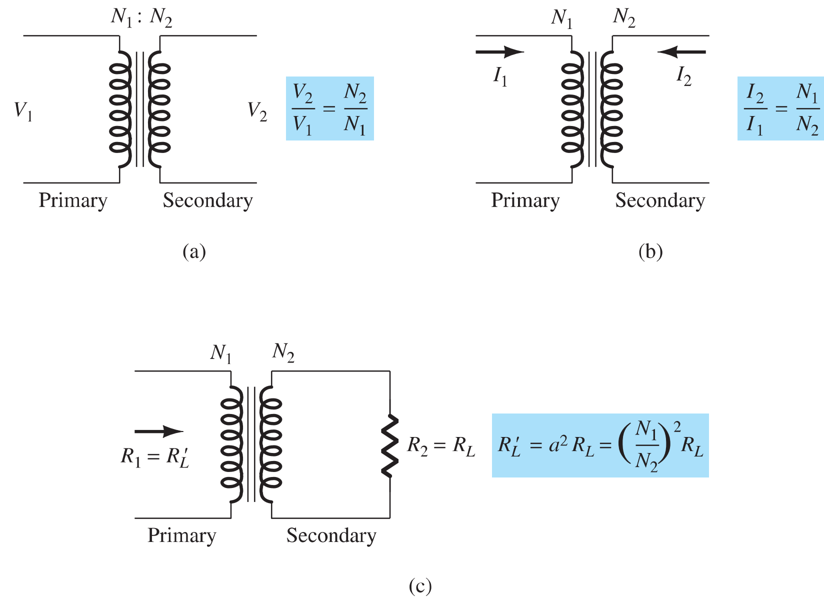

FIG. 12.7
Transformer operation: (a) voltage transformation; (b) current transformation; (c) impedance transformation.

If we define $a = N_1/N_2$, where a is the turns ratio of the transformer, the above equation becomes

$$\frac{R_L'}{R_L} = \frac{R_1}{R_2} = \left(\frac{N_1}{N_2}\right)^2 = a^2 \qquad \textbf{(12.11)}$$

We can express the load resistance reflected to the primary side as

$$R_1 = a^2 R_2 \quad \text{or} \quad R_L' = a^2 R_L \qquad \textbf{(12.12)}$$

where R_L' is the reflected impedance. As shown in Eq. (12.12), the reflected impedance is related directly to the square of the turns ratio. If the number of turns of the secondary is smaller than that of the primary, the impedance seen looking into the primary is larger than that of the secondary by the square of the turns ratio.

EXAMPLE 12.2 Calculate the effective resistance seen looking into the primary of a 15:1 transformer connected to an 8-Ω load.

Solution: Eq. (12.22):

$$R_L' = a^2 R_L = (15)^2 (8\ \Omega) = 1800\ \Omega = \mathbf{1.8\ k\Omega}$$

EXAMPLE 12.3 What transformer turns ratio is required to match a 16-Ω speaker load so that the effective load resistance seen at the primary is 10 kΩ?

Solution: Eq. (12.11):

$$\left(\frac{N_1}{N_2}\right)^2 = \frac{R_L'}{R_L} = \frac{10\ \text{k}\Omega}{16\ \Omega} = 625$$

$$\frac{N_1}{N_2} = \sqrt{625} = \mathbf{25{:}1}$$

Operation of Amplifier Stage

DC Load Line The transformer (dc) winding resistance determines the dc load line for the circuit of Fig. 12.6. Typically, this dc resistance is small (ideally 0 Ω) and, as shown in Fig. 12.8, a 0-Ω dc load line is a straight vertical line. A practical transformer winding resistance would be a few ohms, but only the ideal case will be considered in this discussion. There is no dc voltage drop across the 0-Ω dc load resistance, and the load line is drawn straight vertically from the voltage point, $V_{CE_Q} = V_{CC}$.

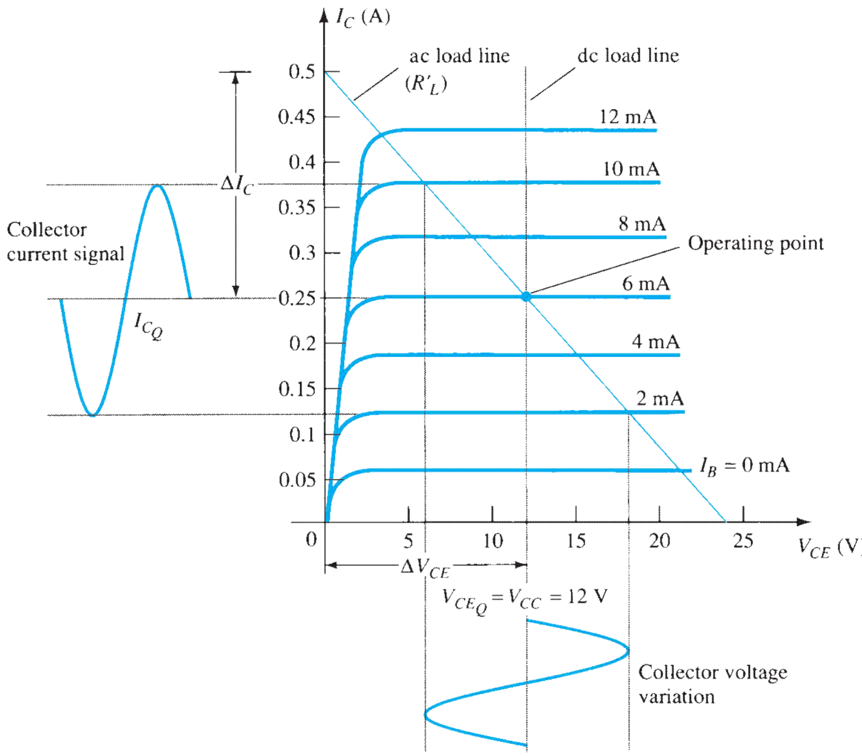

FIG. 12.8
Load lines for class A transformer-coupled amplifier.

Quiescent Operating Point The operating point in the characteristic curve of Fig.12.8 can be obtained graphically at the point of intersection of the dc load line and the base current set by the circuit. The collector quiescent current can then be obtained from the operating point. In class A operation, keep in mind that the dc bias point sets the conditions for the maximum undistorted signal swing for both collector current and collector–emitter voltage. If the input signal produces a voltage swing less than the maximum possible, the efficiency of the circuit at that time will be less than the maximum of 50%. The dc bias point is therefore important in setting the operation of a class A series-fed amplifier.

AC Load Line To carry out ac analysis, it is necessary to calculate the ac load resistance "seen" looking into the primary side of the transformer, then draw the ac load line on the collector characteristic. The reflected load resistance (R'_L) is calculated using Eq. (12.12) using the value of the load connected across the secondary (R_L) and the turns ratio of the transformer. The graphical analysis technique then proceeds as follows. Draw the ac load line so that it passes through the operating point and has a slope equal to $-1/R'_L$ (the reflected load resistance), the load line slope being the negative reciprocal of the ac load resistance. Notice that the ac load line shows that the output signal swing can exceed the value of V_{CC}. In fact, the voltage developed across the transformer primary can be quite large. It is therefore necessary after obtaining the ac load line to check that the possible voltage swing does not exceed transistor maximum ratings.

Signal Swing and Output AC Power Figure 12.9 shows the voltage and current signal swings from the circuit of Fig. 12.6. From the signal variations shown in Fig. 12.9, the values of the peak-to-peak signal swings are

$$V_{CE}(\text{p-p}) = V_{CE_{\max}} - V_{CE_{\min}}$$
$$I_C(\text{p-p}) = I_{C_{\max}} - I_{C_{\min}}$$

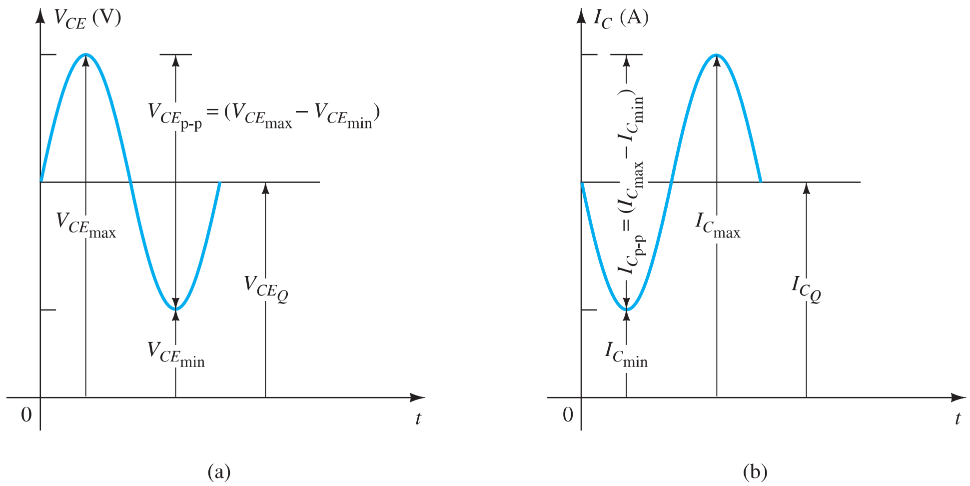

FIG. 12.9
Graphical operation of transformer-coupled class A amplifier.

The ac power developed across the transformer primary can then be calculated using

$$P_o(\text{ac}) = \frac{(V_{CE_{\max}} - V_{CE_{\min}})(I_{C_{\max}} - I_{C_{\min}})}{8} \qquad \textbf{(12.13)}$$

The ac power calculated is that developed across the primary of the transformer. Assuming an ideal transformer (a highly efficient transformer has an efficiency of well over 90%), we find that the power delivered by the secondary to the load is approximately that calculated using Eq. (12.13). The output ac power can also be determined using the voltage delivered to the load.

For the ideal transformer, the voltage delivered to the load can be calculated using Eq. (12.9):

$$V_L = V_2 = \frac{N_2}{N_1}V_1$$

The power across the load can then be expressed as

$$P_L = \frac{V_L^2(\text{rms})}{R_L}$$

and equals the power calculated using Eq. (12.5c).

Using Eq. (12.10) to calculate the load current yields

$$I_L = I_2 = \frac{N_1}{N_2}I_C$$

with the output ac power then calculated using

$$P_L = I_L^2(\text{rms})R_L$$

EXAMPLE 12.4 Calculate the ac power delivered to the 8-Ω speaker for the circuit of Fig. 12.10. The circuit component values result in a dc base current of 6 mA, and the input signal (V_i) results in a peak base current swing of 4 mA.

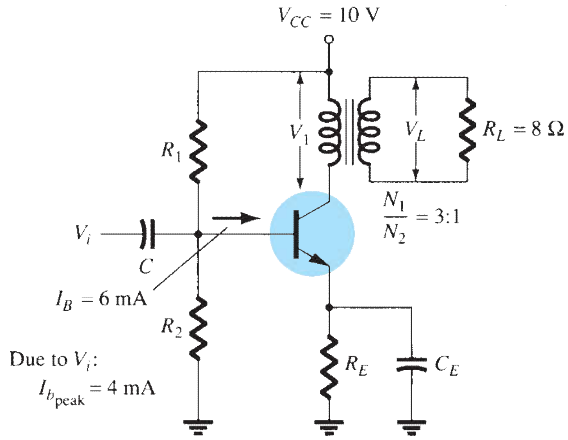

FIG. 12.10
Transformer-coupled class A amplifier for Example 12.4.

Solution: The dc load line is drawn vertically (see Fig. 12.11) from the voltage point:

$$V_{CE_Q} = V_{CC} = 10 \text{ V}$$

For $I_B = 6$ mA, the operating point on Fig. 12.11 is

$$V_{CE_Q} = 10 \text{ V} \quad \text{and} \quad I_{C_Q} = 140 \text{ mA}$$

The effective ac resistance seen at the primary is

$$R'_L = \left(\frac{N_1}{N_2}\right)^2 R_L = (3)^2(8) = 72 \ \Omega$$

The ac load line can then be drawn of slope $-1/72$ going through the indicated operating point. To help draw the load line, consider the following procedure. For a current swing of

$$I_C = \frac{V_{CE}}{R'_L} = \frac{10 \text{ V}}{72 \ \Omega} = 139 \text{ mA}$$

mark a point *A*:

$$I_{CE_Q} + I_C = 140 \text{ mA} + 139 \text{ mA} = 279 \text{ mA along the } y\text{-axis}$$

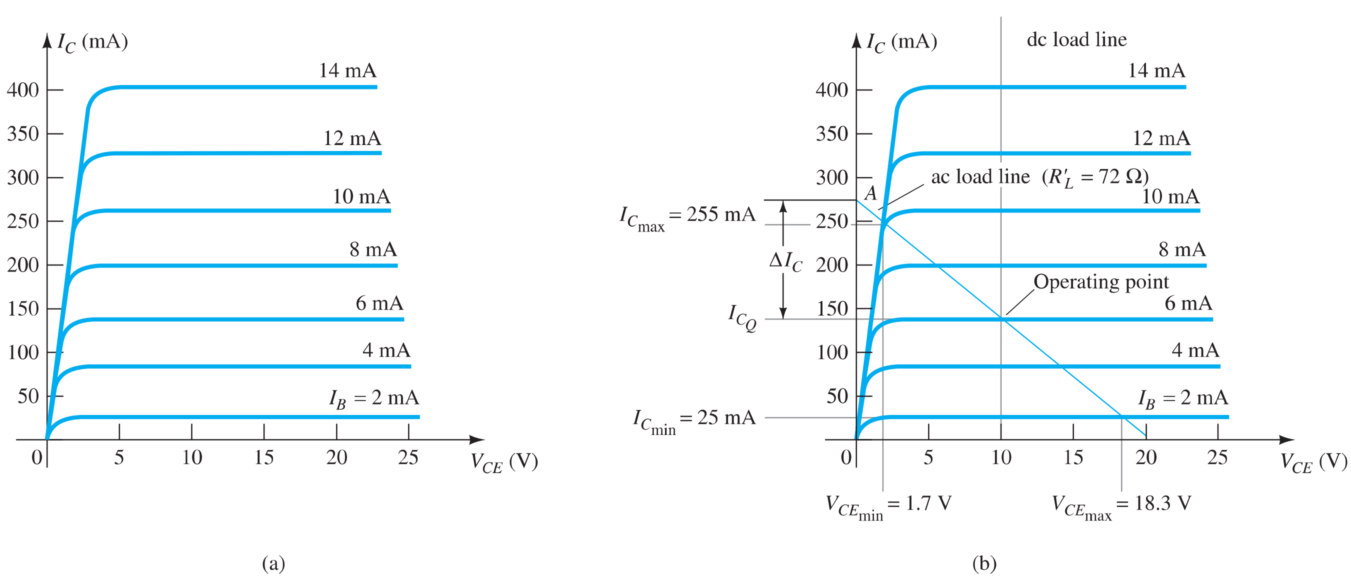

FIG. 12.11
Transformer-coupled class A transistor characteristic for Examples 12.4 and 12.5: (a) device characteristic; (b) dc and ac load lines.

Connect point A through the Q-point to obtain the ac load line. For the given base current swing of 4 mA peak, the maximum and minimum collector current and collector–emitter voltage obtained from Fig. 12.11 are, respectively,

$$V_{CE_{\min}} = 1.7\text{ V} \qquad I_{C_{\min}} = 25\text{ mA}$$
$$V_{CE_{\max}} = 18.3\text{ V} \qquad I_{C_{\max}} = 255\text{ mA}$$

The ac power delivered to the load can then be calculated using Eq. (12.13):

$$P_o(\text{ac}) = \frac{(V_{CE_{\max}} - V_{CE_{\min}})(I_{C_{\max}} - I_{C_{\min}})}{8}$$
$$= \frac{(18.3\text{ V} - 1.7\text{ V})(255\text{ mA} - 25\text{ mA})}{8} = \mathbf{0.477\text{ W}}$$

Efficiency

So far we have considered calculating the ac power delivered to the load. We next consider the input power from the battery, power losses in the amplifier, and the overall power efficiency of the transformer-coupled class A amplifier.

The input (dc) power obtained from the supply is calculated from the supply dc voltage and the average power drawn from the supply:

$$P_i(\text{dc}) = V_{CC}I_{C_Q} \tag{12.14}$$

For the transformer-coupled amplifier, the power dissipated by the transformer is small (due to the small dc resistance of a coil) and will be ignored in the present calculations. Thus the only power loss considered here is that dissipated by the power transistor and calculated using

$$P_Q = P_i(\text{dc}) - P_o(\text{ac}) \tag{12.15}$$

where P_Q is the power dissipated as heat. Although the equation is simple, it is nevertheless significant when operating a class A amplifier. The amount of power dissipated by the transistor is the difference between that drawn from the dc supply (set by the bias point) and the amount delivered to the ac load. When the input signal is very small, with very little ac power delivered to the load, the maximum power is dissipated by the transistor. When the input signal is larger and power delivered to the load is larger, less power is dissipated by the transistor. In other words, the transistor of a class A amplifier has to work hardest (dissipate the most power) when the load is disconnected from the amplifier, and the transistor dissipates the least power when the load is drawing maximum power from the circuit.

EXAMPLE 12.5 For the circuit of Fig. 12.10 and results of Example 12.4, calculate the dc input power, power dissipated by the transistor, and efficiency of the circuit for the input signal of Example 12.4.

Solution: Eq. (12.14):

$$P_i(\text{dc}) = V_{CC}I_{C_Q} = (10\text{ V})(140\text{ mA}) = \mathbf{1.4\text{ W}}$$

Eq. (12.15):

$$P_Q = P_i(\text{dc}) - P_o(\text{ac}) = 1.4\text{ W} - 0.477\text{ W} = \mathbf{0.92\text{ W}}$$

The efficiency of the amplifier is then

$$\%\,\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% = \frac{0.477\text{ W}}{1.4\text{ W}} \times 100\% = \mathbf{34.1\%}$$

Maximum Theoretical Efficiency For a class A transformer-coupled amplifier, the maximum theoretical efficiency goes up to 50%. Based on the signals obtained using the amplifier, the efficiency can be expressed as

$$\% \eta = 50\left(\frac{V_{CE_{max}} - V_{CE_{min}}}{V_{CE_{max}} + V_{CE_{min}}}\right)^2 \% \qquad \textbf{(12.16)}$$

The larger the value of $V_{CE_{max}}$ and the smaller the value of $V_{CE_{min}}$, the closer the efficiency approaches the theoretical limit of 50%.

EXAMPLE 12.6 Calculate the efficiency of a transformer-coupled class A amplifier for a supply of 12 V and outputs of:

a. $V(\text{p}) = 12$ V.
b. $V(\text{p}) = 6$ V.
c. $V(\text{p}) = 2$ V.

Solution:

a. Since $V_{CE_Q} = V_{CC} = 12$ V, the maximum and minimum of the voltage swing are, respectively,

$$V_{CE_{max}} = V_{CE_Q} + V(\text{p}) = 12\text{ V} + 12\text{ V} = 24\text{ V}$$
$$V_{CE_{min}} = V_{CE_Q} - V(\text{p}) = 12\text{ V} - 12\text{ V} = 0\text{ V}$$

resulting in

$$\% \eta = 50\left(\frac{24\text{ V} - 0\text{ V}}{24\text{ V} + 0\text{ V}}\right)^2 \% = \mathbf{50\%}$$

b.

$$V_{CE_{max}} = V_{CE_Q} + V(\text{p}) = 12\text{ V} + 6\text{ V} = 18\text{ V}$$
$$V_{CE_{min}} = V_{CE_Q} - V(\text{p}) = 12\text{ V} - 6\text{ V} = 6\text{ V}$$

resulting in

$$\% \eta = 50\left(\frac{18\text{ V} - 6\text{ V}}{18\text{ V} + 6\text{ V}}\right)^2 \% = \mathbf{12.5\%}$$

c.

$$V_{CE_{max}} = V_{CE_Q} + V(\text{p}) = 12\text{ V} + 2\text{ V} = 14\text{ V}$$
$$V_{CE_{min}} = V_{CE_Q} - V(\text{p}) = 12\text{ V} - 2\text{ V} = 10\text{ V}$$

resulting in

$$\% \eta = 50\left(\frac{14\text{ V} - 10\text{ V}}{14\text{ V} + 10\text{ V}}\right)^2 \% = \mathbf{1.39\%}$$

Notice how dramatically the amplifier efficiency drops from a maximum of 50% for $V(\text{p}) = V_{CC}$ to slightly over 1% for $V(\text{p}) = 2$ V.

12.4 CLASS B AMPLIFIER OPERATION

Class B operation is provided when the dc bias leaves the transistor biased just off, the transistor turning on when the ac signal is applied. This is essentially no bias, and the transistor conducts current for only one-half of the signal cycle. To obtain output for the full cycle of signal, it is necessary to use two transistors and have each conduct on opposite half-cycles, the combined operation providing a full cycle of output signal. Since one part of the circuit pushes the signal high during one half-cycle and the other part pulls the signal low during the other half-cycle, the circuit is referred to as a *push–pull circuit*. Figure 12.12 shows a diagram for push–pull operation. An ac input signal is applied to the push–pull circuit, with each half operating on alternate half-cycles, the load then

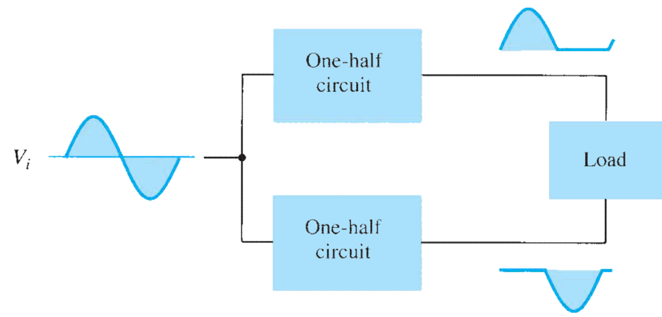

FIG. 12.12
Block representation of push–pull operation.

receiving a signal for the full ac cycle. The power transistors used in the push–pull circuit are capable of delivering the desired power to the load, and the class B operation of these transistors provides greater efficiency than was possible using a single transistor in class A operation.

Input (DC) Power

The power supplied to the load by an amplifier is drawn from the power supply (or power supplies; see Fig. 12.13) that provides the input or dc power. The amount of this input power can be calculated using

$$P_i(\text{dc}) = V_{CC}I_{\text{dc}} \quad \textbf{(12.17)}$$

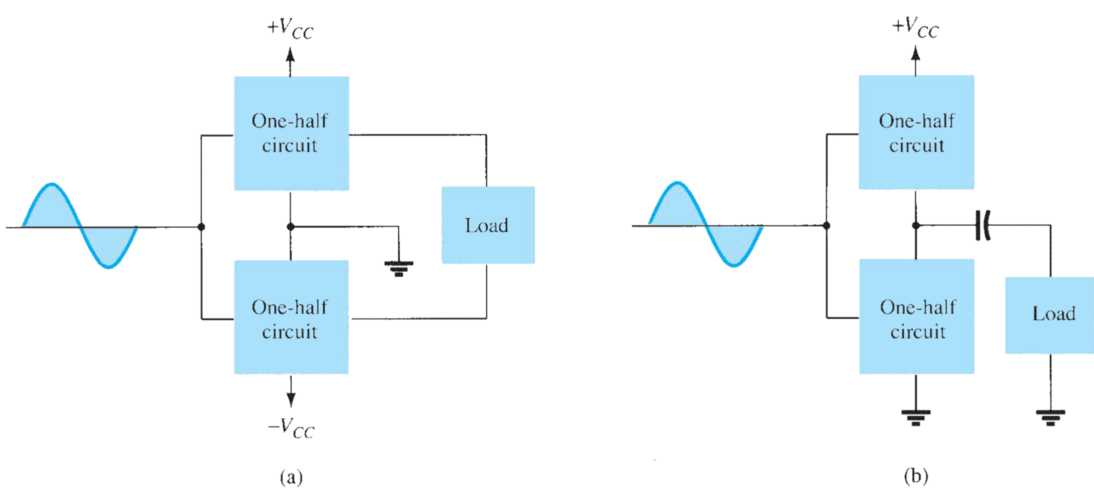

FIG. 12.13
Connection of push–pull amplifier to load: (a) using two voltage supplies; (b) using one voltage supply.

where I_{dc} is the average or dc current drawn from the power supplies. In class B operation, the current drawn from a single power supply has the form of a full-wave rectified signal, whereas that drawn from two power supplies has the form of a half-wave rectified signal from each supply. In either case, the value of the average current drawn can be expressed as

$$I_{\text{dc}} = \frac{2}{\pi}I(\text{p}) \quad \textbf{(12.18)}$$

where $I(\text{p})$ is the peak value of the output current waveform. Using Eq. (12.18) in the power input equation (12.17) results in

$$P_i(\text{dc}) = V_{CC}\left(\frac{2}{\pi}I(\text{p})\right) \tag{12.19}$$

Output (AC) Power

The power delivered to the load (usually referred to as a resistance R_L) can be calculated using any one of a number of equations. If one is using an rms meter to measure the voltage across the load, the output power can be calculated as

$$P_o(\text{ac}) = \frac{V_L^2(\text{rms})}{R_L} \tag{12.20}$$

If one is using an oscilloscope, the measured peak or peak-to-peak output voltage can be used:

$$P_o(\text{ac}) = \frac{V_L^2(\text{p-p})}{8R_L} = \frac{V_L^2(\text{p})}{2R_L} \tag{12.21}$$

The larger the rms or peak output voltage, the larger is the power delivered to the load.

Efficiency

The efficiency of the class B amplifier can be calculated using the basic equation

$$\%\,\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\%$$

Using Eqs. (12.19) and (12.21) in the efficiency equation above results in

$$\%\,\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% = \frac{V_L^2(\text{p})/2R_L}{V_{CC}[(2/\pi)I(\text{p})]} \times 100\% = \frac{\pi}{4}\frac{V_L(\text{p})}{V_{CC}} \times 100\% \tag{12.22}$$

[using $I(\text{p}) = V_L(\text{p})/R_L$]. Equation (12.22) shows that the larger the peak voltage, the higher is the circuit efficiency, up to a maximum value when $V_L(\text{p}) = V_{CC}$, this maximum efficiency then being

$$\text{maximum efficiency} = \frac{\pi}{4} \times 100\% = 78.5\%$$

Power Dissipated by Output Transistors The power dissipated (as heat) by the output power transistors is the difference between the input power delivered by the supplies and the output power delivered to the load,

$$P_{2Q} = P_i(\text{dc}) - P_o(\text{ac}) \tag{12.23}$$

where P_{2Q} is the power dissipated by the two output power transistors. The dissipated power handled by each transistor is then

$$P_Q = \frac{P_{2Q}}{2} \tag{12.24}$$

EXAMPLE 12.7 For a class B amplifier providing a 20-V peak signal to a 16-Ω load (speaker) and a power supply of $V_{CC} = 30$ V, determine the input power, output power, and circuit efficiency.

Solution: A 20-V peak signal across a 16-Ω load provides a peak load current of

$$I_L(\text{p}) = \frac{V_L(\text{p})}{R_L} = \frac{20\ \text{V}}{16\ \Omega} = 1.25\ \text{A}$$

The dc value of the current drawn from the power supply is then

$$I_{\text{dc}} = \frac{2}{\pi} I_L(\text{p}) = \frac{2}{\pi}(1.25\ \text{A}) = 0.796\ \text{A}$$

and the input power delivered by the supply voltage is

$$P_i(\text{dc}) = V_{CC} I_{\text{dc}} = (30\ \text{V})(0.796\ \text{A}) = \mathbf{23.9\ W}$$

The output power delivered to the load is

$$P_o(\text{ac}) = \frac{V_L^2(\text{p})}{2R_L} = \frac{(20\ \text{V})^2}{2(16\ \Omega)} = \mathbf{12.5\ W}$$

for a resulting efficiency of

$$\%\,\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% = \frac{12.5\ \text{W}}{23.9\ \text{W}} \times 100\% = \mathbf{52.3\%}$$

Maximum Power Considerations

For class B operation, the maximum output power is delivered to the load when $V_L(\text{p}) = V_{CC}$:

$$\text{maximum } P_o(\text{ac}) = \frac{V_{CC}^2}{2R_L} \tag{12.25}$$

The corresponding peak ac current $I(\text{p})$ is then

$$I(\text{p}) = \frac{V_{CC}}{R_L}$$

so that the maximum value of average current from the power supply is

$$\text{maximum } I_{\text{dc}} = \frac{2}{\pi} I(\text{p}) = \frac{2V_{CC}}{\pi R_L}$$

Using this current to calculate the maximum value of input power results in

$$\text{maximum } P_i(\text{dc}) = V_{CC}(\text{maximum } I_{\text{dc}}) = V_{CC}\left(\frac{2V_{CC}}{\pi R_L}\right) = \frac{2V_{CC}^2}{\pi R_L} \tag{12.26}$$

The maximum circuit efficiency for class B operation is then

$$\text{maximum } \%\,\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% = \frac{V_{CC}^2/2R_L}{V_{CC}[(2/\pi)(V_{CC}/R_L)]} \times 100\%$$

$$= \frac{\pi}{4} \times 100\% = \mathbf{78.54\%} \tag{12.27}$$

When the input signal results in less than the maximum output signal swing, the circuit efficiency is less than 78.5%.

For class B operation, the maximum power dissipated by the output transistors does not occur at the maximum power input or output condition. The maximum power dissipated by the two output transistors occurs when the output voltage across the load is

$$V_L(\text{p}) = 0.636 V_{CC} \qquad \left(= \frac{2}{\pi} V_{CC}\right)$$

for a maximum transistor power dissipation of

$$\text{maximum } P_{2Q} = \frac{2V_{CC}^2}{\pi^2 R_L} \tag{12.28}$$

EXAMPLE 12.8 For a class B amplifier using a supply of $V_{CC} = 30$ V and driving a load of 16 Ω, determine the maximum input power, output power, and transistor dissipation.

Solution: The maximum output power is

$$\text{maximum } P_o(\text{ac}) = \frac{V_{CC}^2}{2R_L} = \frac{(30\text{ V})^2}{2(16\ \Omega)} = \mathbf{28.125\ W}$$

The maximum input power drawn from the voltage supply is

$$\text{maximum } P_i(\text{dc}) = \frac{2V_{CC}^2}{\pi RL} = \frac{2(30\text{ V})^2}{\pi(16\ \Omega)} = \mathbf{35.81\ W}$$

The circuit efficiency is then

$$\text{maximum } \%\,\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% = \frac{28.125\text{ W}}{35.81\text{ W}} \times 100\% = 78.54\%$$

as expected. The maximum power dissipated by each transistor is

$$\text{maximum } P_Q = \frac{\text{maximum } P_{2Q}}{2} = 0.5\left(\frac{2V_{CC}^2}{\pi^2 R_L}\right) = 0.5\left[\frac{2(30\text{ V})^2}{\pi^2 16\ \Omega}\right] = \mathbf{5.7\ W}$$

Under maximum conditions a pair of transistors each handling 5.7 W at most can deliver 28.125 W to a 16-Ω load while drawing 35.81 W from the supply.

The maximum efficiency of a class B amplifier can also be expressed as follows:

$$P_o(\text{ac}) = \frac{V_L^2(\text{p})}{2R_L}$$

$$P_i(\text{dc}) = V_{CC}I_{\text{dc}} = V_{CC}\left[\frac{2V_L(\text{p})}{\pi R_L}\right]$$

so that

$$\%\,\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% = \frac{V_L^2(\text{p})/2R_L}{V_{CC}[(2/\pi)(V_L(\text{p})/R_L)]} \times 100\%$$

$$\%\,\eta = 78.54\frac{V_L(\text{p})}{V_{CC}}\% \qquad \textbf{(12.29)}$$

EXAMPLE 12.9 Calculate the efficiency of a class B amplifier for a supply voltage of $V_{CC} = 24$ V with peak output voltages of:

a. $V_L(\text{p}) = 22$ V.
b. $V_L(\text{p}) = 6$ V.

Solution: Using Eq. (12.29) gives

a. $\%\,\eta = 78.54\dfrac{V_L(\text{p})}{V_{CC}}\% = 78.54\left(\dfrac{22\text{ V}}{24\text{ V}}\right) = \mathbf{72\%}$

b. $\%\,\eta = 78.54\left(\dfrac{6\text{ V}}{24\text{ V}}\right)\% = \mathbf{19.6\%}$

Notice that a voltage near the maximum [22 V in part (a)] results in an efficiency near the maximum, whereas a small voltage swing [6 V in part (b)] still provides an efficiency near 20%. Similar power supply and signal swings would have resulted in much poorer efficiency in a class A amplifier.

12.5 CLASS B AMPLIFIER CIRCUITS

A number of circuit arrangements for obtaining class B operation are possible. We will consider the advantages and disadvantages of a number of the more popular circuits in this section. The input signals to the amplifier could be a single signal, the circuit then