

# POWER AMPLIFIERS

## 15.1 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 the present chapter, we concentrate on those 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 full  $360^\circ$  of the cycle. Figure 15.1 a shows that this requires the

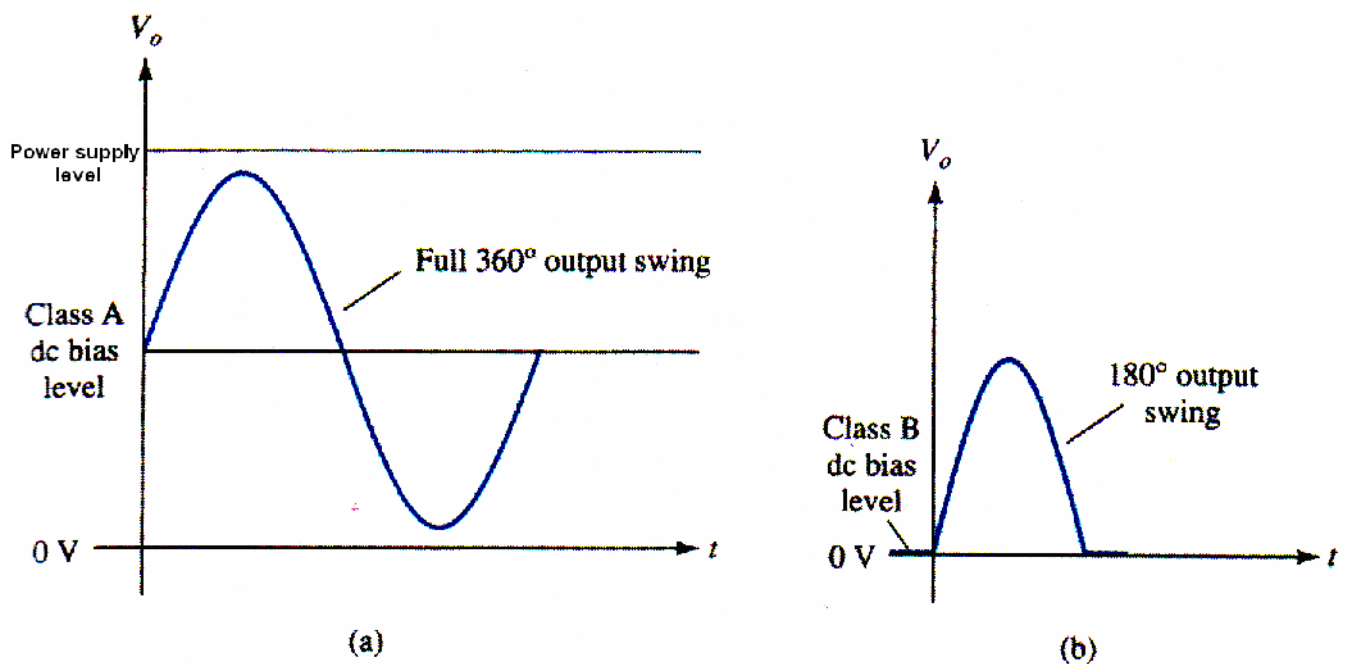


Fig 15.1 Amplifier operation classes

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 input signal cycle, or for  $180^\circ$  of signal, as shown in Fig. 15.1 b. The dc bias point for class B is therefore at 0 V, with the output then varying from this bias point for a half-cycle. Obviously, the 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  $360^\circ$  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  $180^\circ$  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  $180^\circ$  and  $360^\circ$  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  $180^\circ$  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 communication.

**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.

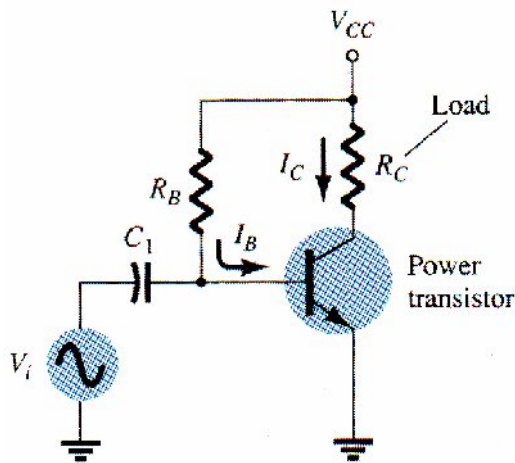
## Amplifier Efficiency

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

## 15.2 SERIES-FED CLASS A AMPLIFIER

This simple fixed-bias circuit connection shown in Fig. 15.2 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 15.2 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

$$I_B = \frac{V_{CC} - 0.7 \text{ V}}{R_B} \quad (15.1)$$

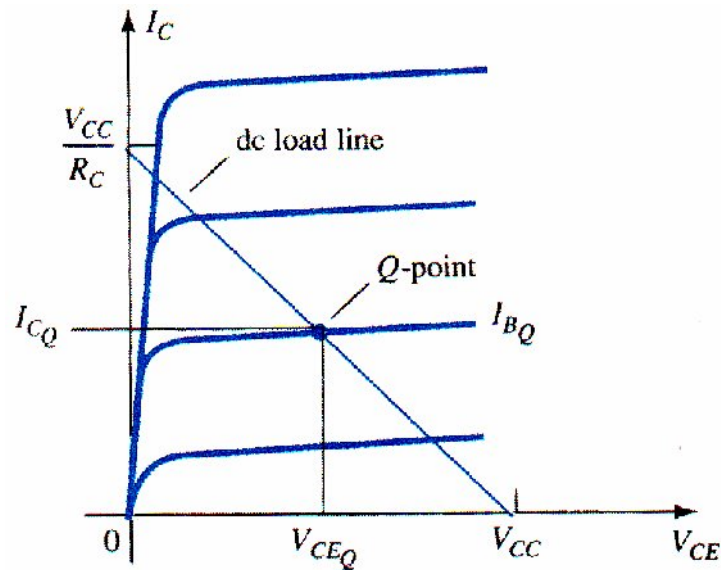
With the collector current then being

$$I_C = \beta I_B \quad (15.2)$$

With the collector-emitter voltage then

$$V_{CE} = V_{CC} - I_C R_C \quad (15.3)$$

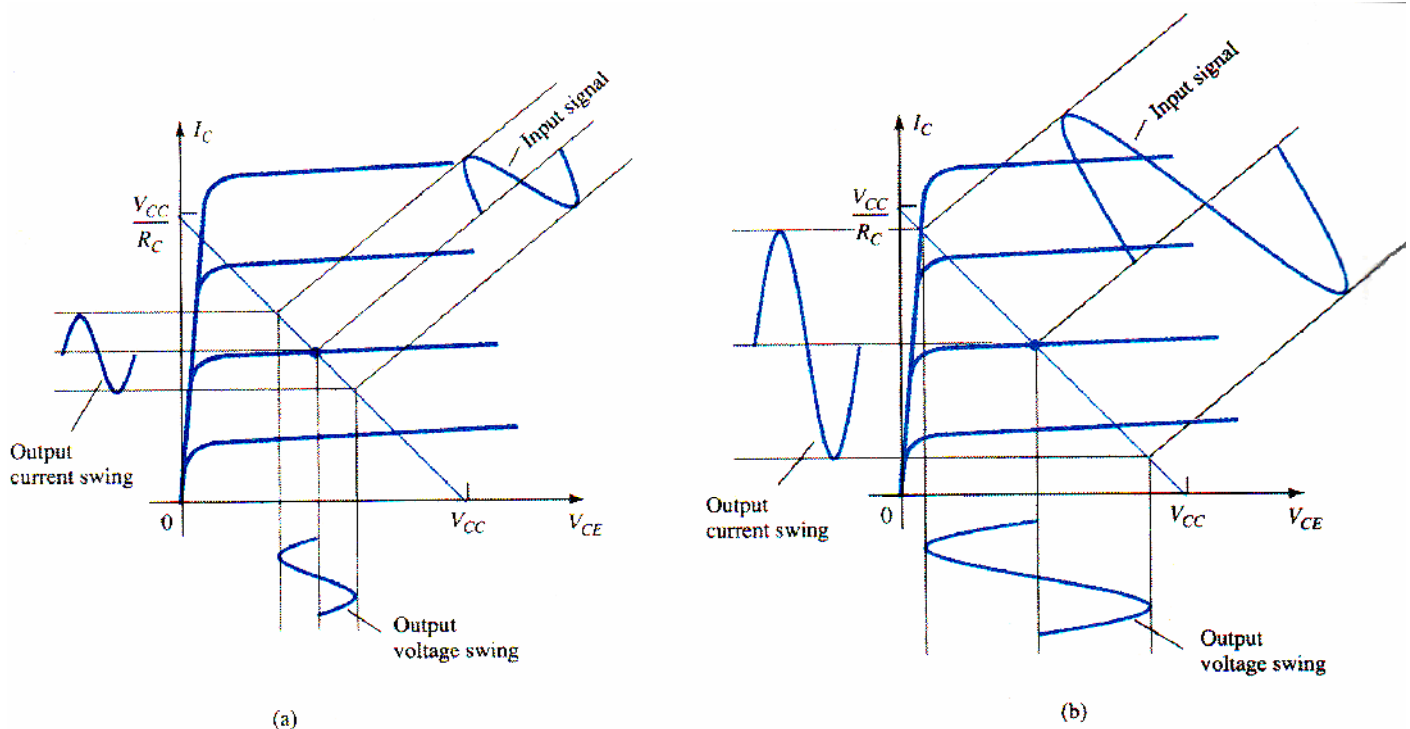
To appreciate the importance of the dc bias on the operation of the power amplifier, consider the collector characteristic shown in Fig. 15.3. An ac load line is drawn using the values of  $V_{CC}$  and  $R_C$ . The intersection of the dc bias value of  $I_B$  with the dc load line then determines the operating point (Q-point) for the circuit. The quiescent point values are those calculated using Eqs. (15.1) through (15.3). 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. 15.2 are determined as described below.



**Fig 15.3** Transistor characteristic showing load line and Q-point

### AC Operation

When an input ac signal is applied to the amplifier of Fig. 15.2, the output will vary from its dc bias operating voltage and current. A small input signal, as shown in Fig. 15.4, 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.



**Fig 15.4** Amplifier input and output signal variation

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,  $V_{CC}$

### **Power Consideration**

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

$$P_i(\text{dc}) = V_{CC}I_{CQ} \quad (15.4)$$

Even with an ac signal applied, the average current drawn from the supply remains the same, so that Eq. (15.4) 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. 15.2. The ac signal,  $V_i$ , causes the base current to vary around the dc bias current and the collector current around its quiescent level,  $I_{CQ}$ . As shown in Fig. 15.4, the ac input signal result in ac current and ac voltage signals. The larger the input signal, the larger 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:

$$P_o(\text{ac}) = V_{CE}(\text{rms})I_C(\text{rms}) \quad (15.5a)$$

$$P_o(\text{ac}) = I_C^2(\text{rms})R_C \quad (15.5b)$$

$$P_o(\text{ac}) = \frac{V_C^2(\text{rms})}{R_C} \quad (15.5c)$$

**Using peak signals:** The ac power delivered to the load may be expressed using

$$P_o(\text{ac}) = \frac{V_{CE}(\text{p})I_C(\text{p})}{2} \quad (15.6a)$$

$$P_o(\text{ac}) = \frac{V_{CE}^2(\text{p})}{2R_C} \quad (15.6c)$$



**Using peak-to-peak signals:** The ac power delivered to the load may be expressed using

$$P_o(\text{ac}) = \frac{V_{CE}(\text{p-p})I_C(\text{p-p})}{8} \quad (15.7a)$$

$$P_o(\text{ac}) = \frac{I_C^2(\text{p-p})}{8} R_C \quad (15.7b)$$

$$P_o(\text{ac}) = \frac{V_{CE}^2(\text{p-p})}{8R_C} \quad (15.7c)$$

### 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

$$\% \eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% \quad (15.8)$$

### 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.(15.7a) yields

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

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

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

We can then use Eq. (15.8) to calculate the maximum efficiency:

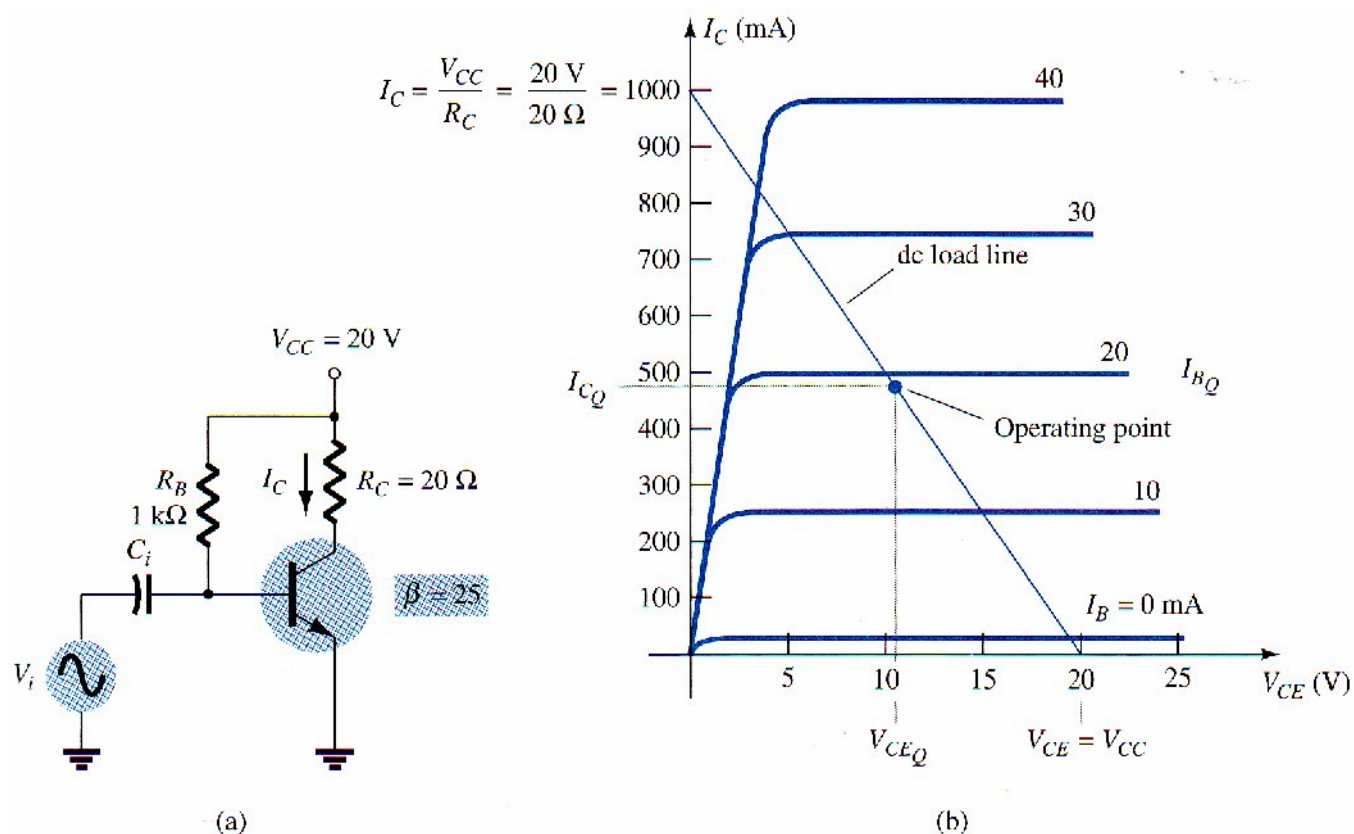
$$\begin{aligned}\text{maximum } \% \eta &= \frac{\text{maximum } P_o(\text{ac})}{\text{maximum } P_i(\text{dc})} \times 100\% \\ &= \frac{V_{CC}^2/8R_C}{V_{CC}^2/2R_C} \times 100\% \\ &= 25\%\end{aligned}$$

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 15.1**

Calculate the input power, output power, and efficiency of the amplifier circuit in Fig. 15.5 for an input voltage that results in a base current of 10 mA peak.





**Fig 15.5 Operation of a series-fed circuit for Example 15.1**

### Solution

Using Eqs. (15.1) through (15.3), the Q-point can be determined to be

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

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

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

This bias point is marked on the transistor collector characteristic of Fig. 15.5b. The ac variation of the output signal can be obtained graphically using the dc load line drawn on Fig. 15.5b by connecting  $V_{CE} = V_{CC} = 20\text{ V}$  with  $I_C = V_{CC}/R_C = 1000\text{ mA} = 1\text{ A}$ , as shown. When the input ac base current increases from its dc bias level, the collector current rises by

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

Using Eq. (15.6b) yields

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

Using Eq. (15.4) results in

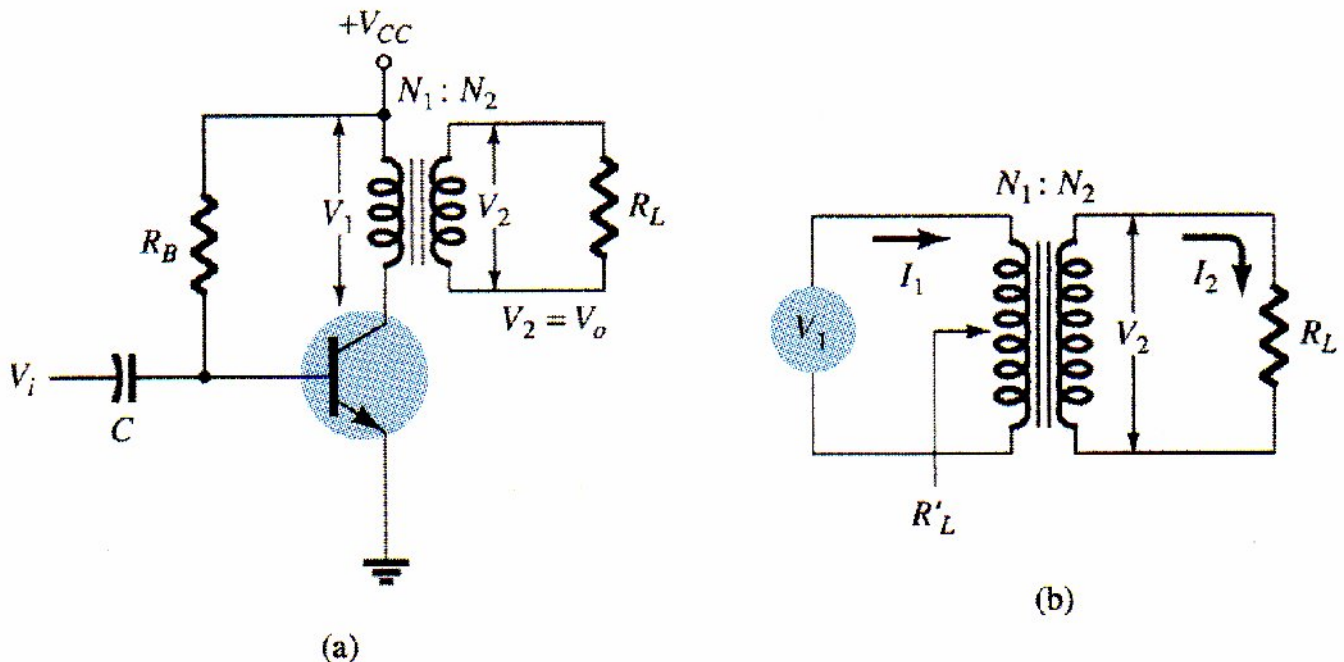
$$P_i(\text{dc}) = V_{CC}I_{C_Q} = (20 \text{ V})(0.48 \text{ A}) = \mathbf{9.6 \text{ W}}$$

The amplifier's power efficiency can then be calculated using Eq. (15.8):

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

### 15.3 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. 15.6. This is a simple circuit form to use in presenting a few basic concepts. More practical circuit versions are covered later. 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.



**Fig 15.6 Transformer-coupled audio power amplifier**

#### 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. 15.7a, 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

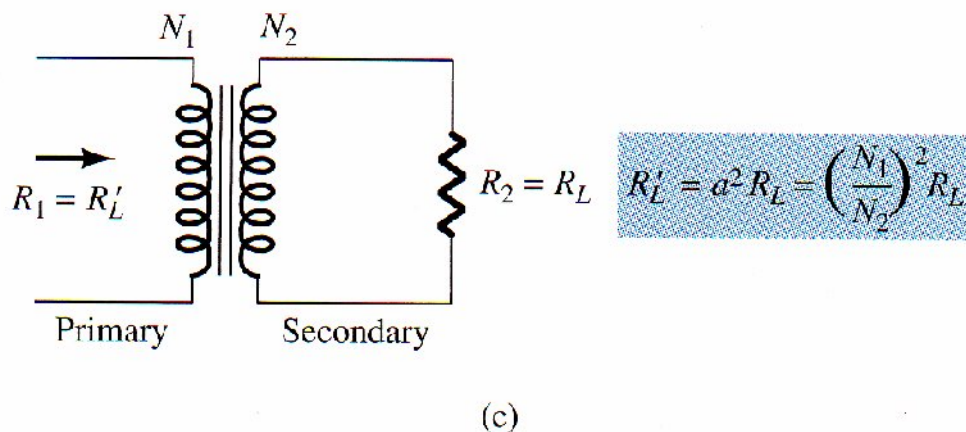
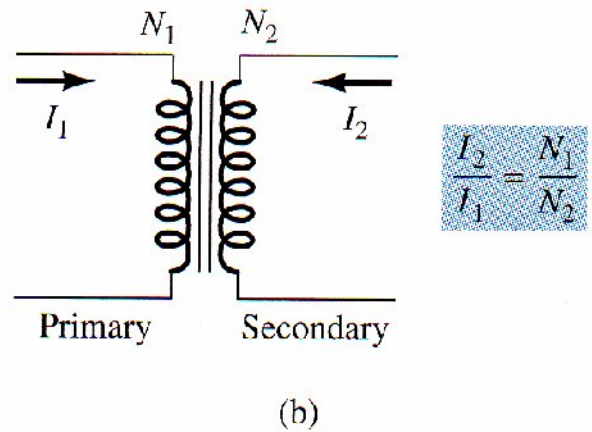
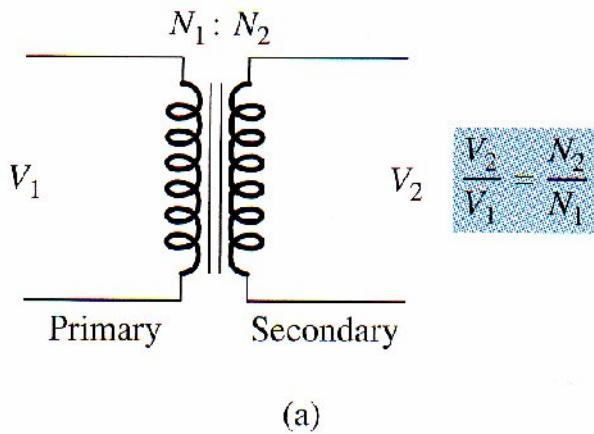
$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \quad (15.9)$$

Equation (15.9) shows that if the number of turns of wire on the secondary side is larger than 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 turns in the windings. The current transformation is given by

$$\frac{I_2}{I_1} = \frac{N_1}{N_2} \quad (15.10)$$



**Fig 15.7 Transformer operation: (a) voltage transformation; (b) current transformation; (c) impedance transformation**

This relationship is shown in Fig. 15.7b. 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, impedance 'seen' from either side (primary or secondary) can also be changed. As shown in Fig. 15.7c, 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:

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

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

$$\frac{R'_L}{R_L} = \frac{R_1}{R_2} = \left(\frac{N_1}{N_2}\right)^2 = a^2 \quad (15.11)$$

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

$$R_1 = a^2 R_2 \quad \text{or} \quad R'_L = a^2 R_L \quad (15.12)$$

Where  $R'_L$  is the reflected impedance, as shown in Eq. (15.12), 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 15.2

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

**Solution**

$$\text{Eq. (15.12): } R'_L = a^2 R_L = (15)^2 (8 \, \Omega) = 1800 \, \Omega = \mathbf{1.8 \, k\Omega}$$

#### EXAMPLE 15.3

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**



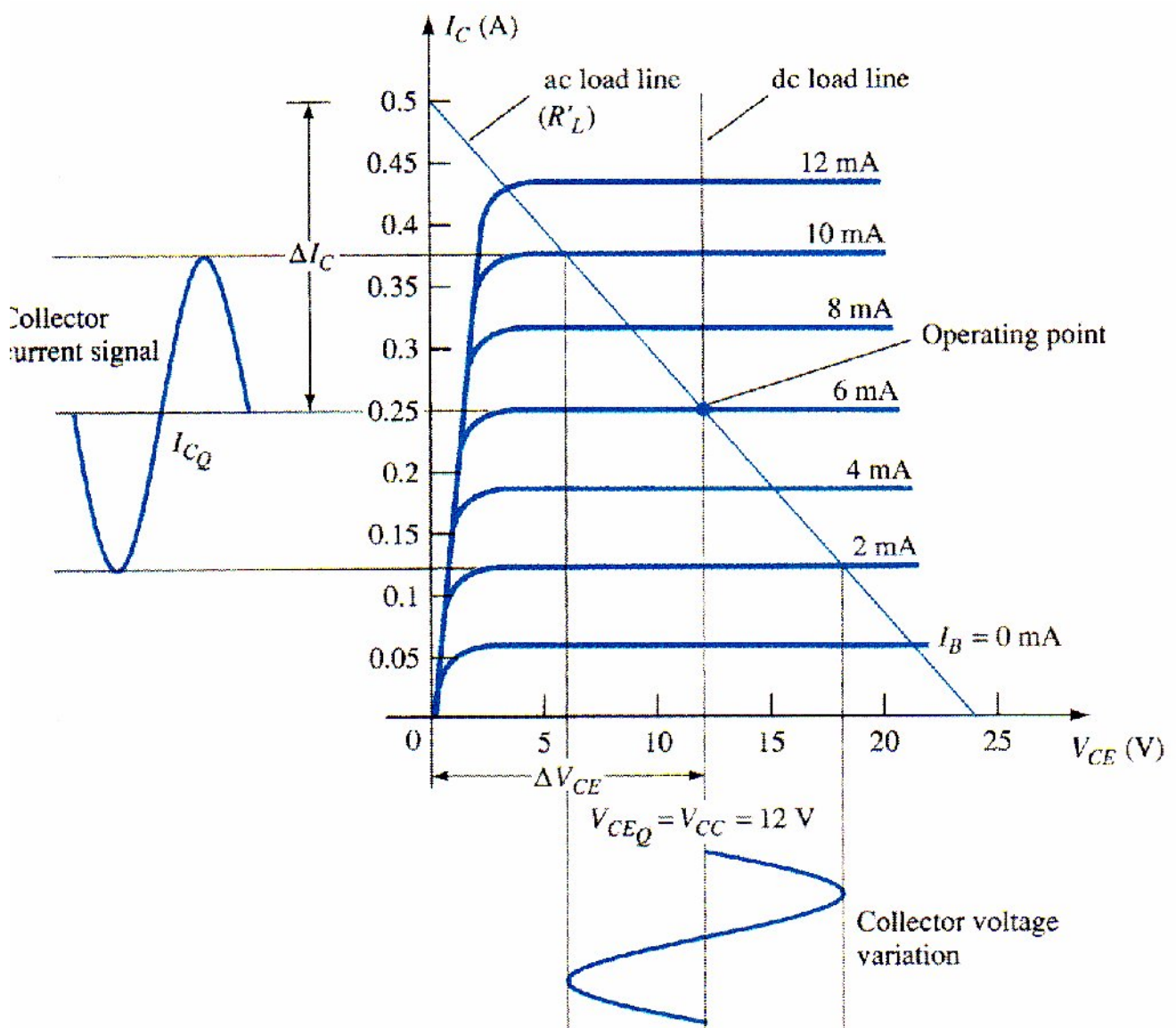
$$\text{Eq. (15.11): } \left( \frac{N_1}{N_2} \right)^2 = \frac{R'_L}{R_L} = \frac{10 \text{ k}\Omega}{16 \Omega} = 625$$

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

## Operation of Amplifier Stage

### DC LOAD LINE

The transformer (dc) winding resistance determines the dc load line for the circuit of Fig. 15.6. Typically, this dc resistance is small (ideally 0  $\Omega$ ) and, as shown in Fig. 15.8, a 0- $\Omega$  dc load line is a straight vertical line,



**Fig 15.8 Load lines for class A transformer-coupled amplifier**

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 load line is drawn straight vertically from the voltage point,  $V_{CEQ} = V_{CC}$

### QUIESCENT OPERATING POINT

The operating point in the characteristic curve of Fig. 15.8 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 25%. 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. (15.12) 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 15.9 shows the voltage and current signal swings from the circuit of Fig. 15.6. From the signal variations shown in Fig. 15.9, the values of the peak-to-peak signal swings are

$$V_{CE}(p-p) = V_{CE_{max}} - V_{CE_{min}}$$

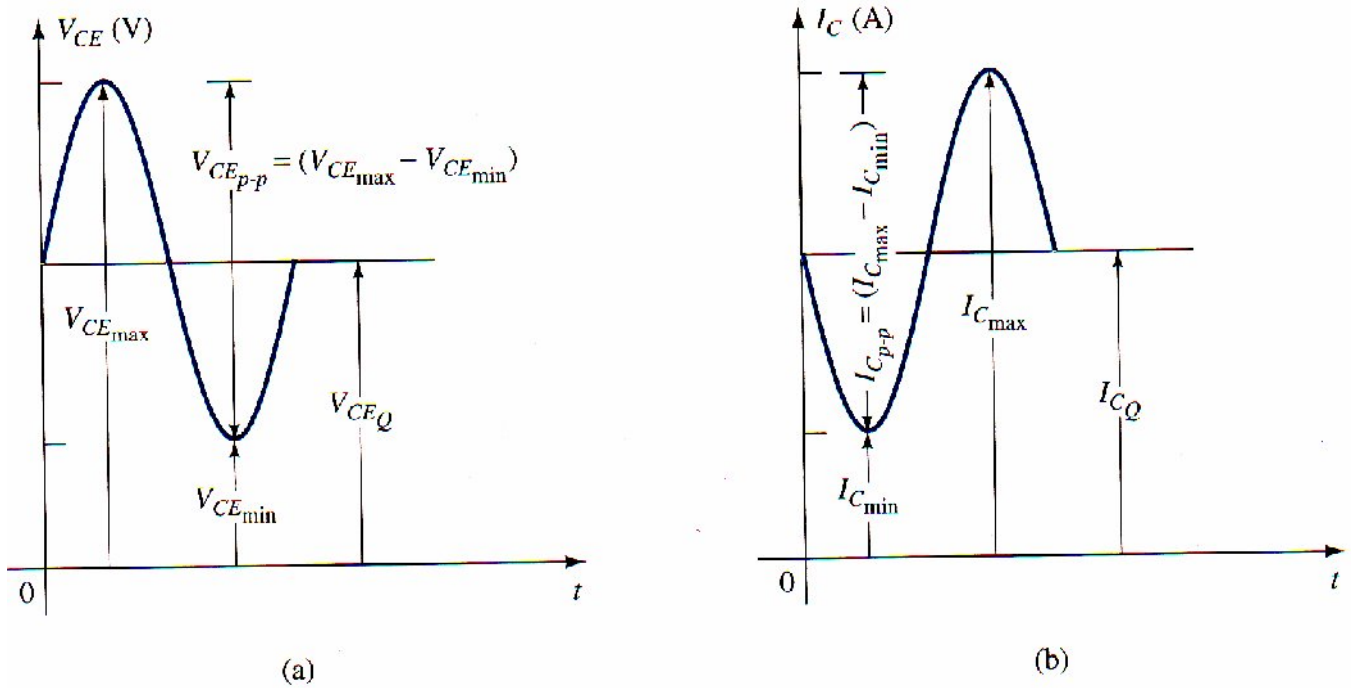
$$I_C(p-p) = I_{C_{max}} - I_{C_{min}}$$

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

$$P_o(ac) = \frac{(V_{CE_{max}} - V_{CE_{min}})(I_{C_{max}} - I_{C_{min}})}{8} \quad (15.13)$$



The ac power calculated is that developed across the primary of the transformer. As summing an ideal transformer (a highly efficient transformer has an efficiency of well over 90%), the power delivered by the secondary to the load is approximately that calculated using Eq. (15.13). The output ac power can also be determined using the voltage delivered to the load.



**Fig 15.9 Graphical operation of transformer-coupled class A amplifier**

For the ideal transformer, the voltage delivered to the load can be calculated using Eq. (15.9):

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

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. (15.5c).

Using Eq. (15.10) 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 15.4

Calculate the ac power delivered to the 8- $\Omega$  speaker for the circuit of Fig.15.10. 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.

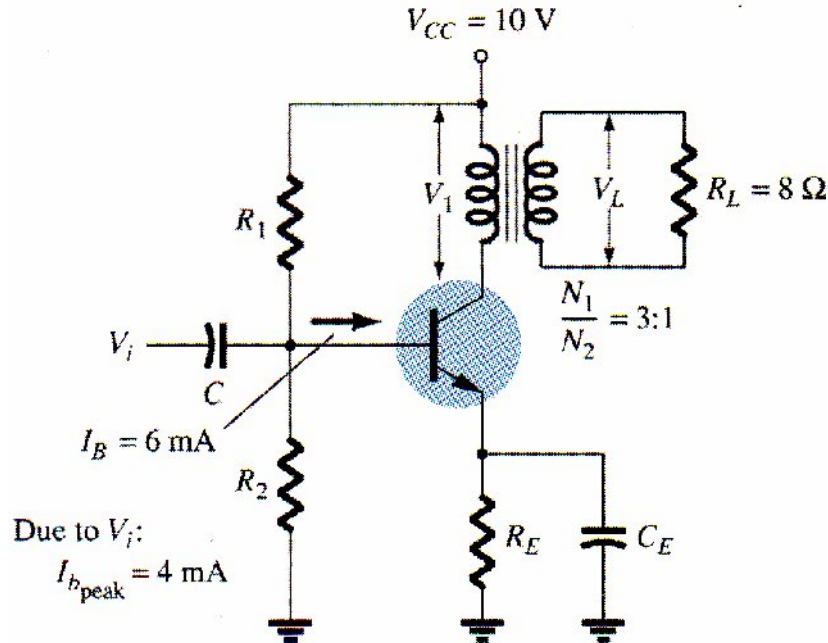


Fig 15.10 Transformer-coupled class A amplifier for Example 15.4

#### Solution

The dc load line is drawn vertically (see Fig. 15.11) from the voltage point:

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

For  $I_B = 6 \text{ mA}$ , the operating point on Fig. 15.11 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

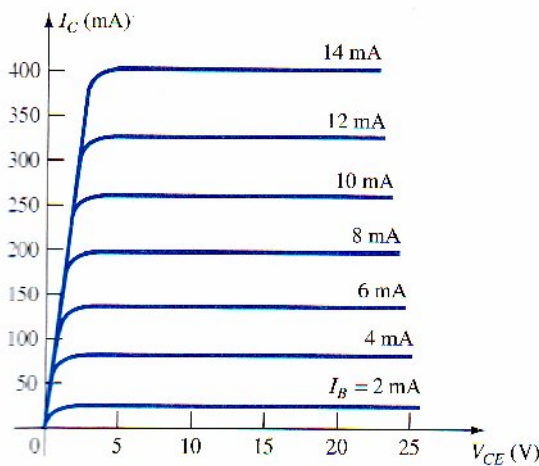
$$R'_L = \left( \frac{N_1}{N_2} \right)^2 R_L = (3)^2 (8) = 72 \Omega$$

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

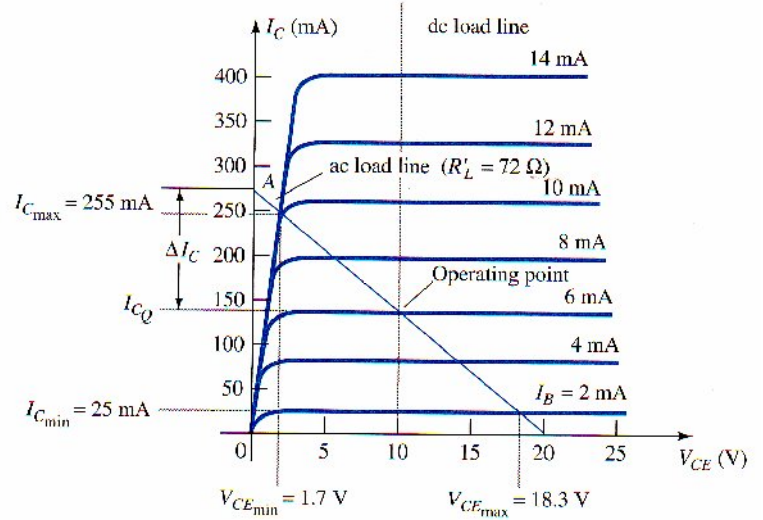
$$I_C = \frac{V_{CE}}{R'_L} = \frac{10 \text{ V}}{72 \Omega} = 139 \text{ mA}$$

Mark a point (A):

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



(a)



(b)

**Fig 15.11 Transformer-coupled class A transistor characteristic for Examples 15.4 and 15.5: (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. 15.11 are

$$\begin{aligned} V_{CE_{min}} &= 1.7 \text{ V} & I_{C_{min}} &= 25 \text{ mA} \\ V_{CE_{max}} &= 18.3 \text{ V} & I_{C_{max}} &= 255 \text{ mA} \end{aligned}$$

The ac power delivered to the load can then be calculated using Eq. (15.13):

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

### 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 efficiency of the transformer-coupled class A amplifier. The input (dc) power obtained from the supply is calculated from the supply dc voltage and average power drawn from the supply:

$$P_i(\text{dc}) = V_{CC}I_{C_Q} \quad (15.14)$$

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

$$P_Q = P_i(\text{dc}) - P_o(\text{ac}) \quad (15.15)$$

Where  $P_Q$  is the power dissipated as heat. While 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 15.5

For the circuit of Fig. 15.10 and results of Example 15.4, calculate the dc input power. Power dissipated by the transistor, and efficiency of the circuit for the input signal of Example 15.4.

#### Solution

$$\text{Eq. (15.14): } P_i(\text{dc}) = V_{CC}I_{C_Q} = (10 \text{ V})(140 \text{ mA}) = \mathbf{1.4 \text{ W}}$$

$$\text{Eq. (15.15): } P_Q = P_i(\text{dc}) - P_o(\text{ac}) = 1.4 \text{ W} - 0.477 \text{ W} = \mathbf{0.92 \text{ W}}$$

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

$$\% \eta = 50 \left( \frac{V_{CE_{\max}} - V_{CE_{\min}}}{V_{CE_{\max}} + V_{CE_{\min}}} \right)^2 \quad (15.16)$$

The larger the value of  $V_{CE_{\max}}$ , and the smaller the value of  $V_{CE_{\min}}$  the closer the efficiency approach

the theoretical limit of 50%.

### EXAMPLE 15.6

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

(a)  $V(p) = 12V$ .

(b)  $V(p) = 6V$ .

(c)  $V(p) = 2V$ .

### Solution

Since  $V_{CEQ} = V_{CC} = 12 V$ , the maximum and minimum of the voltage swing are

$$(a) \quad V_{CE_{max}} = V_{CEQ} + V(p) = 12 V + 12 V = 24 V$$

$$V_{CE_{min}} = V_{CEQ} - V(p) = 12 V - 12 V = 0 V$$

Resulting in

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

$$(b) \quad V_{CE_{max}} = V_{CEQ} + V(p) = 12 V + 6 V = 18 V$$

$$V_{CE_{min}} = V_{CEQ} - V(p) = 12 V - 6 V = 6 V$$

Resulting in

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

$$(c) \quad V_{CE_{max}} = V_{CEQ} + V(p) = 12 V + 2 V = 14 V$$

$$V_{CE_{min}} = V_{CEQ} - V(p) = 12 V - 2 V = 10 V$$

Resulting in

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

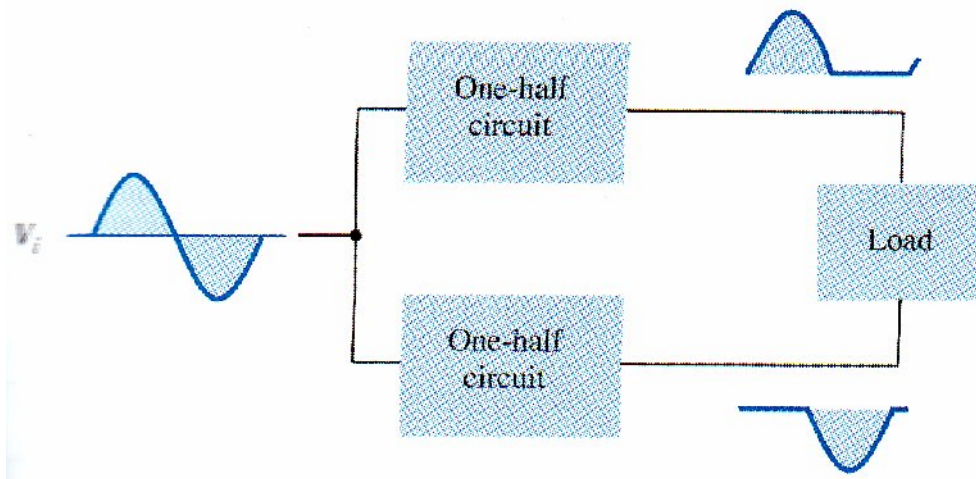
Notice how dramatically the amplifier efficiency drops from a maximum of 50% for  $V(p) = V_{CC}$  to slightly over 1% for  $V(p) = 2V$

## 15.4 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 15.12 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 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 is possible using a single transistor in class A operation



**Fig 15.12 Block representation of push-pull operation**

#### Input (DC) Power

The power supplied to the load by an amplifier is drawn from the power supply (or power supplies; see Fig. 15.13) that provides the input or dc power. The amount of this input power can be calculated using

$$P_i(\text{dc}) = V_{CC}I_{\text{dc}} \quad (15.17)$$

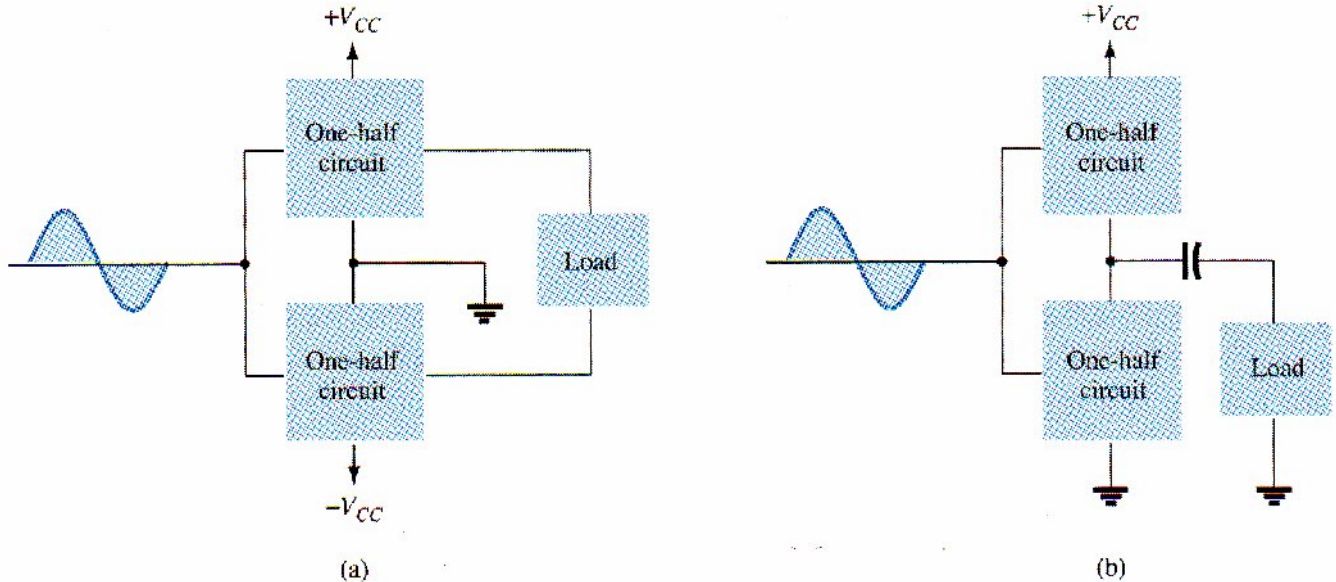
Where  $I_{\text{dc}}$  is the average or dc current drawn from the power supplies. In class B operation, the current drawn from a single power supply has the form of a full-wave rectified signal, while that drawn from two power supplies has the form of a half-wave rectified signal from each supply.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

$$I_{\text{dc}} = \frac{2}{\pi} I(\text{p}) \quad (15.18)$$

Where  $I(\text{p})$  is the peak value of the output current waveform. Using Eq. (15.18) in the power input equation (Eq. 15.17) results in



$$P_i(\text{dc}) = V_{CC} \left( \frac{2}{\pi} I(p) \right) \quad (15.19)$$



**Fig 15.13 Connection of push-pull amplifier to load: (a) using two voltage supplies; (b) using one voltage supply**

### Output (AC) Power

The power delivered to the load (usually referred to as a resistance,  $R_L$ ) can be calculated using anyone 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

$$P_o(\text{ac}) = \frac{V_L^2(\text{rms})}{R_L} \quad (15.20)$$

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

$$P_o(\text{ac}) = \frac{V_L^2(\text{p-p})}{8R_L} = \frac{V_L^2(\text{p})}{2R_L} \quad (15.21)$$

The larger the rms or peak output voltage, the larger 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. (15.19) and (15.21) in the efficiency equation above results in

$$\% \eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% = \frac{V_L^2(p)/2R_L}{V_{CC}[(2/\pi)I(p)]} \times 100\% = \frac{\pi}{4} \frac{V_L(p)}{V_{CC}} \times 100\% \quad (15.22)$$

(Using  $I(p) = V_L(p)/R_L$ ). Equation (15.22) shows that the larger the peak voltage, the higher the circuit efficiency, up to a maximum value when  $V_L(p) = V_{CC}$ , 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.

$$P_{2Q} = P_i(\text{dc}) - P_o(\text{ac}) \quad (15.23)$$

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

$$P_Q = \frac{P_{2Q}}{2} \quad (15.24)$$

### EXAMPLE 15.7

For a class B amplifier providing a 20-V peak signal to a 16-Ω load (speaker) and a power supply of  $V_{CC} = 30 \text{ V}$ , 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

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

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

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

And the input power delivered by the supply voltage is

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

The output power delivered to the load is

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

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  $V_L(p) = V_{CC}$

$$\text{maximum } P_o(\text{ac}) = \frac{V_{CC}^2}{2R_L} \quad (15.25)$$

The corresponding peak ac current  $I(p)$  is then

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

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

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

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

$$\text{maximum } P_i(\text{dc}) = V_{CC}(\text{maximum } I_{dc}) = V_{CC} \left( \frac{2V_{CC}}{\pi R_L} \right) = \frac{2V_{CC}^2}{\pi R_L} \quad (15.26)$$

The maximum circuit efficiency for class B operation is then

$$\begin{aligned} \text{maximum } \% \eta &= \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% = \frac{V_{CC}^2/2R_L}{V_{CC}[(2/\pi)(V_{CC}/R_L)]} \times 100\% \\ &= \frac{\pi}{4} \times 100\% = \mathbf{78.54\%} \end{aligned} \quad (15.27)$$

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

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

For a maximum transistor power dissipation of

$$\text{maximum } P_{2Q} = \frac{2V_{CC}^2}{\pi^2 R_L} \quad (15.28)$$

### EXAMPLE 15.8

For a class B amplifier using a supply of  $V_{CC} = 30 \text{ V}$  and driving a load of  $16\Omega$ . Determine the maximum input power, output power, and transistor dissipation

#### Solution

The maximum output power is

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

The maximum input power drawn from the voltage supply is

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

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

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

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

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

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

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

So that



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

$$\% \eta = 78.54 \frac{V_L(p)}{V_{CC}} \% \quad (15.29)$$

### EXAMPLE 15.9

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

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

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

### Solution

Using Eq. (15.29) gives

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

$$(b) \% \eta = 78.54 \left( \frac{6 \text{ V}}{24 \text{ V}} \right) \% = 19.6 \%$$

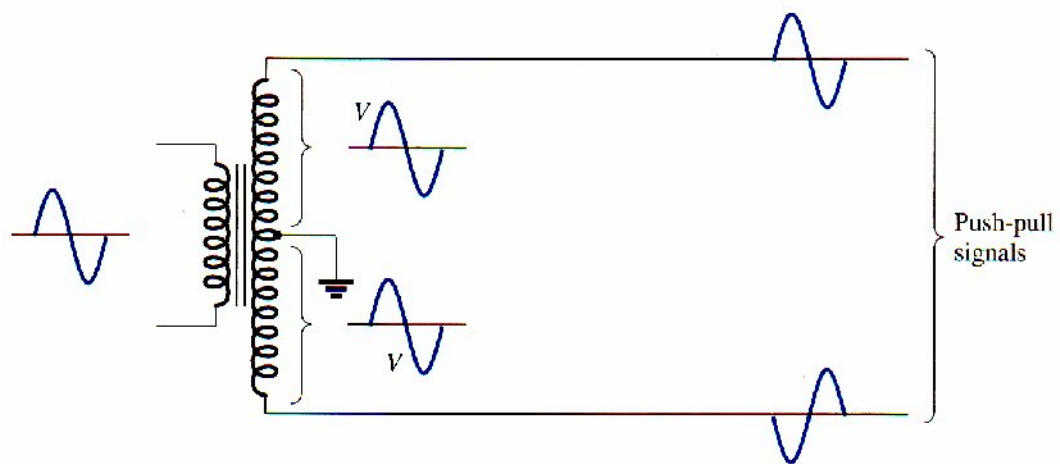
Notice that a voltage near the maximum [22 V in part (a)] results in an efficiency near the maximum, while a small voltage swing [6 V in part (b)] still provides an efficiency near 20%. Similar power supply and signal swings would have resulted in much poorer efficiency in a class A amplifier.

## 15.5 CLASS B AMPLIFIER CIRCUITS

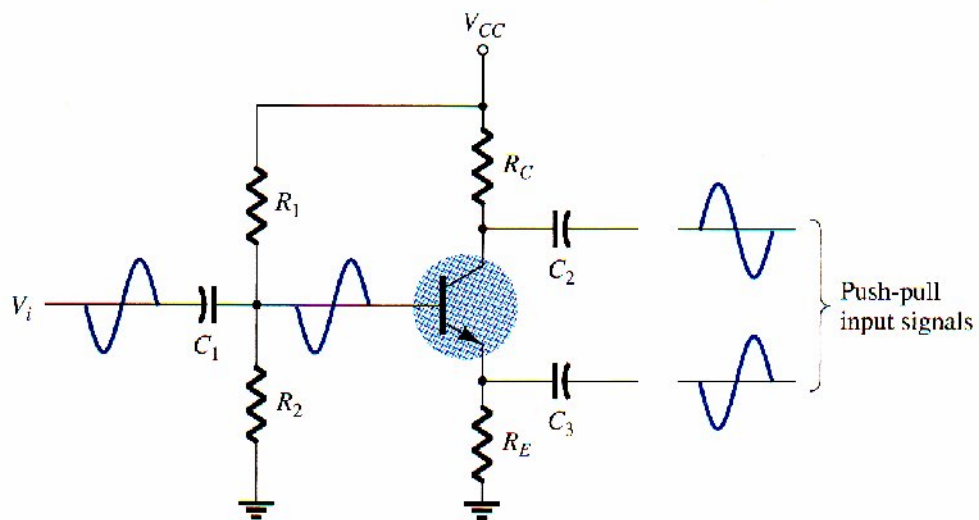
A number of circuit arrangements for obtaining class B operation are possible. We will consider the advantages and disadvantages of a number of the more popular circuits this section. The input signals to the amplifier could be a single signal, the circuit then providing two different output stages, each operating for one-half the cycle. If the input is in the form of two opposite polarity signals, two similar stages, could be used, each operating on the alternate cycle because of the input signal. One means of obtaining polarity or phase inversion is using a transformer, the transformer-coupled amplifier having been very popular for a long time.

Opposite polarity input, can easily be obtained using an op-amp having two opposite outputs or using a few op-amp stages to obtain two opposite polarity signals, an opposite polarity operation can also be achieved using a single input and complementary transistors (nnp and pnp, or nMOS and pMOS).

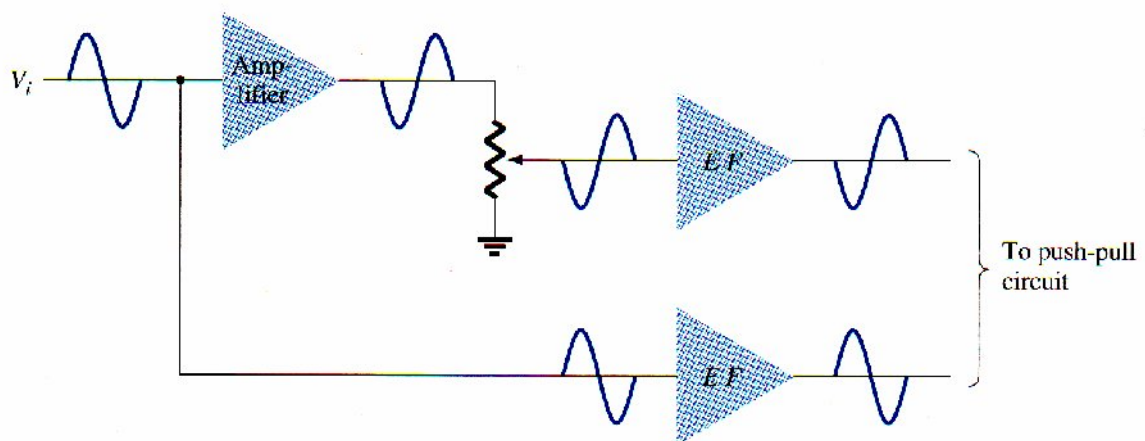
Figure 15.14 shows different ways to obtain phase-inverted signals from a single input signal. Figure 15.14a shows a center-tapped transformer to provide opposite phase signals. If the transformer is exactly center-tapped, the two signals are exactly opposite in phase and of the same magnitude.



(a)



(b)



(c)

**Fig 15.14 Phase-splitter circuit**

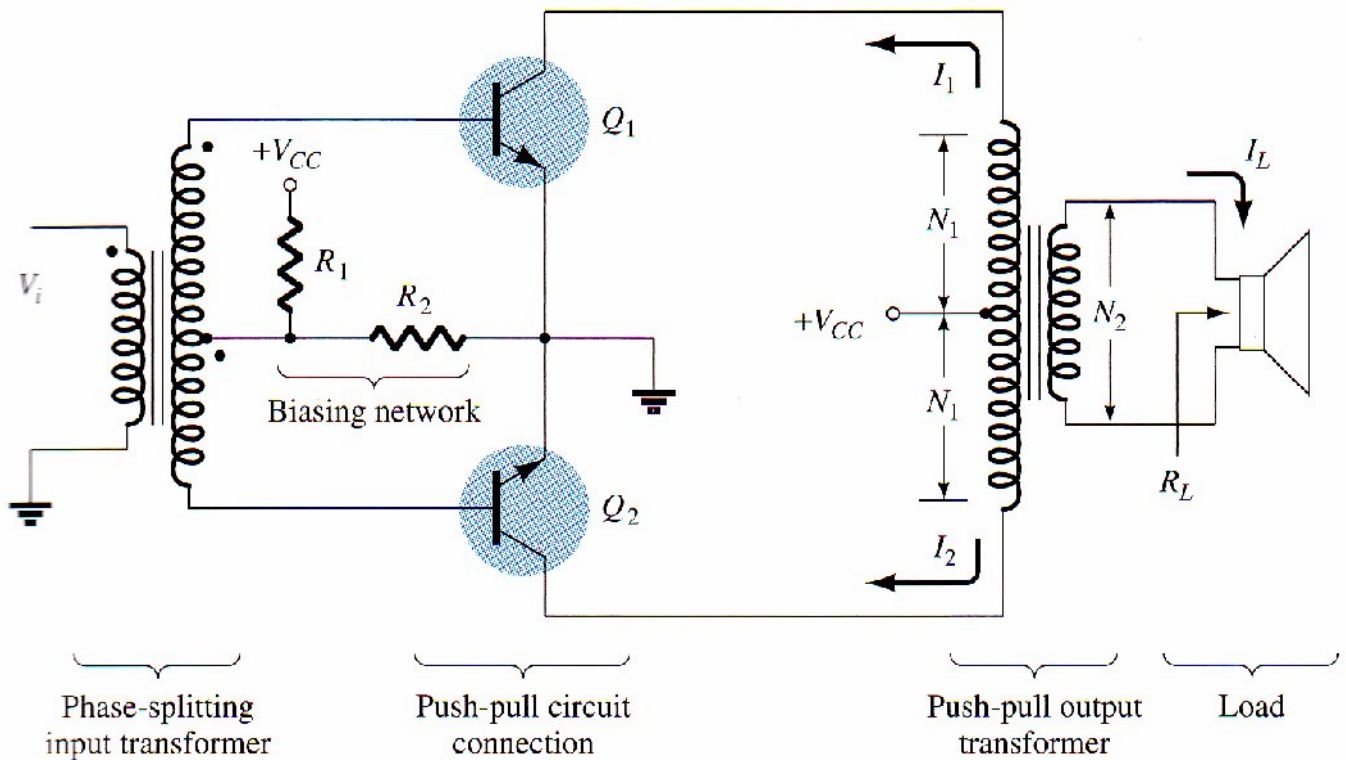


The circuit of Fig. 15.14b uses a BJT stage with in-phase output from the emitter and opposite phase output from the collector. If the gain is made nearly 1 for each output the same magnitude results. Prob-ably most common would be using op-amp stages, one to provide an inverting gain of unity and the other a non inverting gain of unity, to provide two outputs of the same magnitude but of opposite phase.

### Transformer-Coupled Push-Pull Circuits

The circuit of Fig. 15.15 uses a center-tapped input transformer to produce opposite polarity signals to the two transistor inputs and an output transformer to drive the load in a push-pull mode of operation described next.

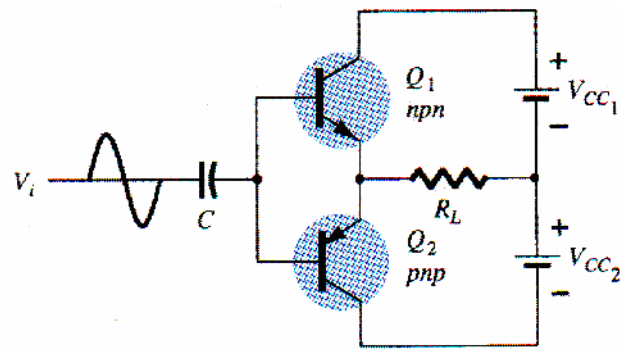
During the first half-cycle of operation, transistor  $Q_1$  is driven into conduction whereas transistor  $Q_2$  is driven off. The current  $I_1$  through the transformer results in the first half-cycle of signal to the load. During the second half-cycle of the input signal.  $Q_2$  conducts whereas  $Q_1$  stays off, the current  $I_2$  through the transformer resulting in the second half-cycle to the load, the overall signal developed across the load then varies over the full cycle of signal operation.



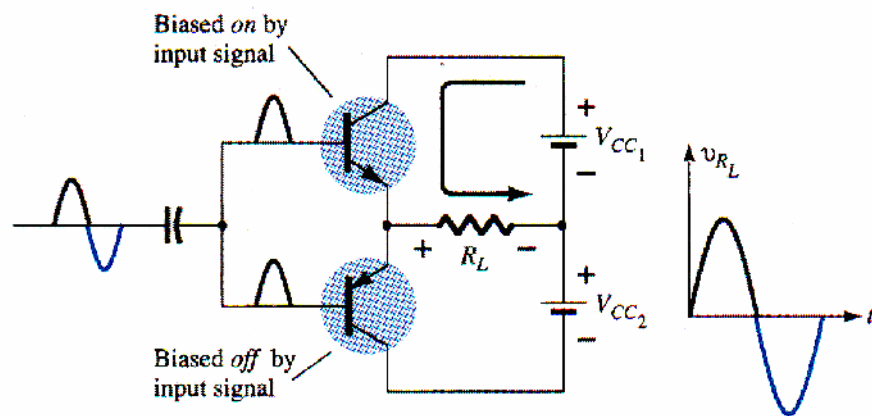
**Fig 15.15 Push-pull circuit**

### Complementary-Symmetry Circuits

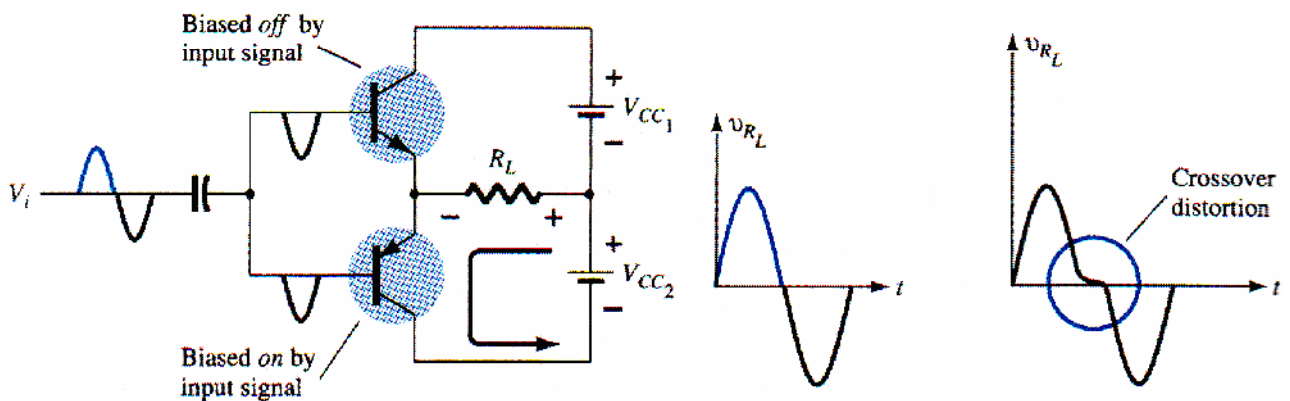
Using complementary transistors (nnp and npn) it is possible to obtain a full cycle output across a load using half-cycles of operation from each transistor, as shown in Fig. 15.16a.



(a)



(b)



(c)

(d)

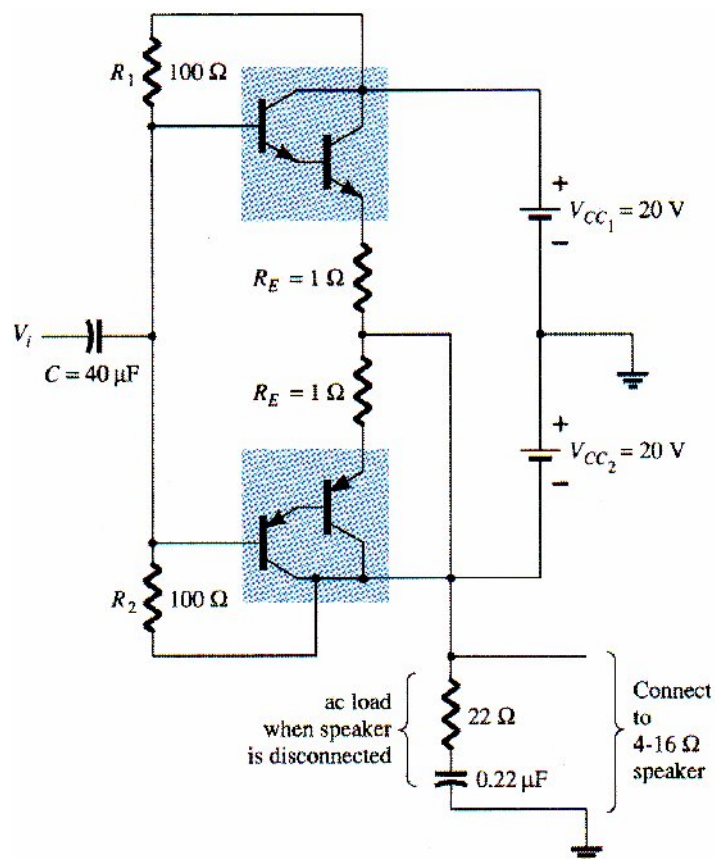
**Fig 15.16 Complementary-symmetry push-pull circuit**

While a single input signal is applied to the base of both transistors, the transistors, being of opposite

type, will conduct on opposite half-cycles of the input. The npn transistor will be biased into conduction by the positive half-cycle of signal, with a resulting half-cycle of signal across the load as shown in Fig. 15.16b. During the negative half-cycle of signal, the pnp transistor is biased into conduction when the input goes negative, as shown in Fig. 15.16c.

During a complete cycle of the input, a complete cycle of output signal is developed across the load. One disadvantage of the circuit is the need for two separate voltage supplies. Another, less obvious disadvantage with the complementary circuit is shown in the resulting crossover distortion in the output signal (see Fig. 15.16d). Crossover distortion refers to the fact that during the signal crossover from positive to negative (or vice versa) there is some nonlinearity in the output signal. This results from the fact that the circuit does not provide exact switching of one transistor off and the other on at the zero-voltage condition. Both transistors may be partially off so that the output voltage does not follow the input around the zero-voltage condition. Biasing the transistors in class AB improves this operation by biasing both transistors to be on for more than half a cycle.

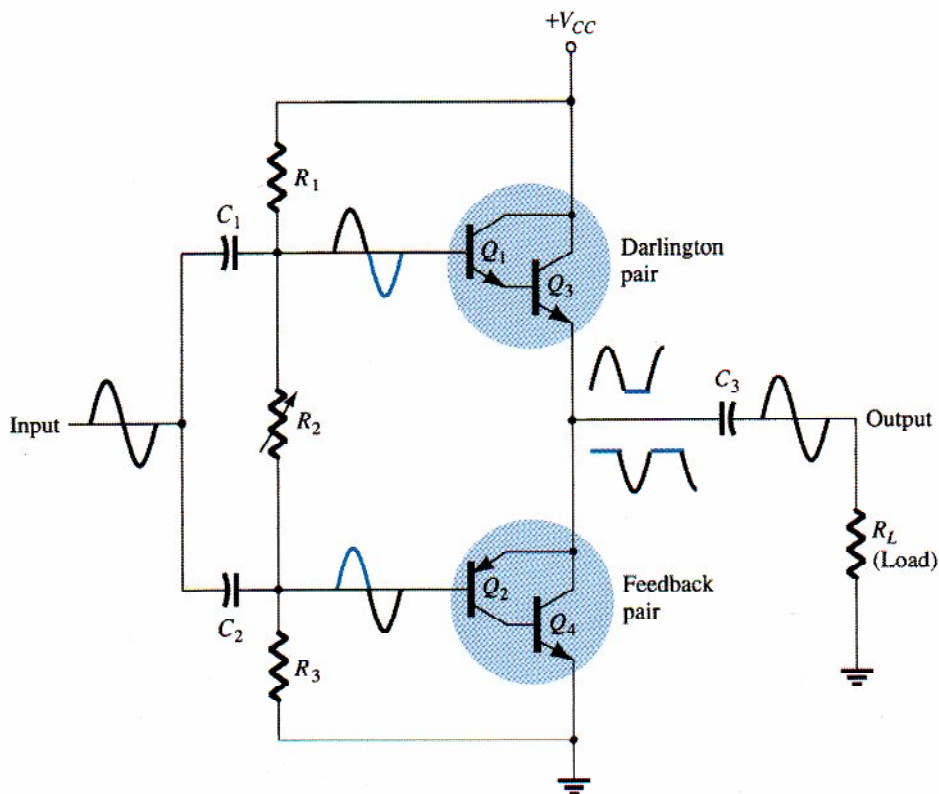
A more practical version of a push-pull circuit using complementary transistors is shown in Fig. 15.17. Note that the load is driven as the output of an emitter-follower so that the load resistance of the load is matched by the low output resistance of the driving source. The circuit uses complementary Darlington-connected transistors to provide higher output current and lower output resistance.



**Fig 15.17 Complementary-symmetry push-pull circuit using Darlington transistors**

### Quasi-Complementary Push-Pull Amplifier

In practical power amplifier circuits, it is preferable to use npn transistors for both high-current-output devices. Since the push-pull connection requires complementary devices, a pnp high-power transistor must be used. A practical means of obtaining complementary operation while using the same, matched npn transistors for the output is provided by a quasi-complementary circuit, as shown in Fig. 15.18.

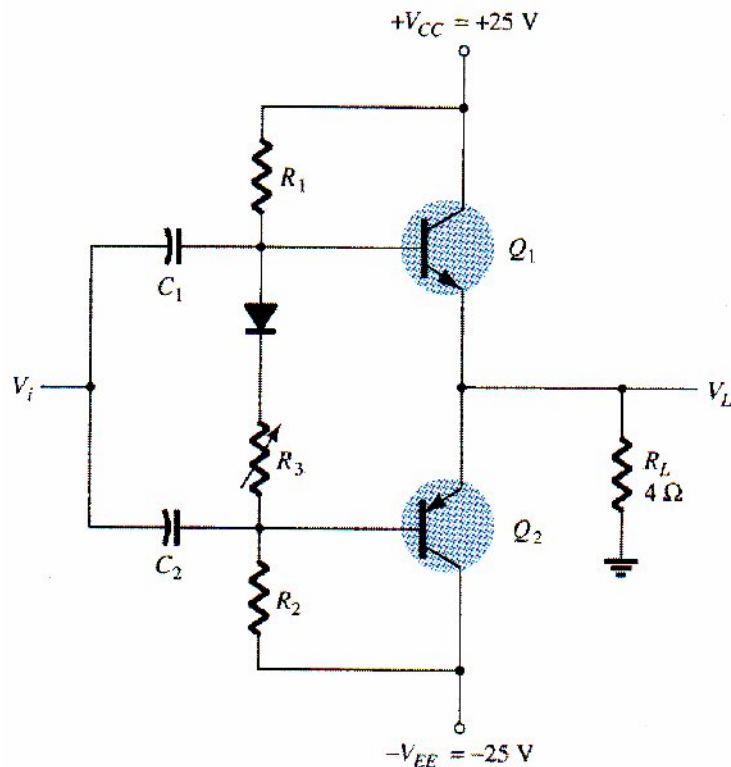


**Fig 15.18 Quasi-complementary push-pull transformerless power amplifier**

The push-pull operation is achieved by using complementary transistors ( $Q_1$  and  $Q_2$ ) before the matched npn output transistors ( $Q_3$  and  $Q_4$ ). Notice that transistors  $Q_1$  and  $Q_3$  form a Darlington connection that provides output from a low-impedance emitter-follower. The connection of transistors  $Q_2$  and  $Q_4$  forms a feedback pair, which similarly provides a low-impedance drive to the load. Resistor  $R_2$  can be adjusted to minimize crossover distortion by adjusting the dc bias condition. The single input signal applied to the push-pull stage then results in a full cycle output to the load. The quasi-complementary push-pull amplifier is presently the most popular form of power amplifier

#### EXAMPLE 15.10

For the circuit of Fig. 15.19, calculate the input power, output power, and power handled by each output transistor and the circuit efficiency for an input of 12 V rms.



**Fig 15.19 Class B power amplifier for Example 15.10-15.12**

**Solution**

The peak input voltage is

$$V_i(p) = \sqrt{2} V_i(\text{rms}) = \sqrt{2} (12 \text{ V}) = 16.97 \text{ V} \approx 17 \text{ V}$$

Since the resulting voltage across the load is ideally the same as the input signal (the amplifier has, ideally, a voltage gain of unity),

$$V_L(p) = 17 \text{ V}$$

and the output power developed across the load is

$$P_o(\text{ac}) = \frac{V_L^2(p)}{2R_L} = \frac{(17 \text{ V})^2}{2(4 \Omega)} = 36.125 \text{ W}$$

The peak load current is

$$I_L(p) = \frac{V_L(p)}{R_L} = \frac{17 \text{ V}}{4 \Omega} = 4.25 \text{ A}$$

from which the dc current from the supplies is calculated to be

$$I_{dc} = \frac{2}{\pi} I_L(p) = \frac{2(4.25 \text{ A})}{\pi} = 2.71 \text{ A}$$

so that the power supplied to the circuit is

$$P_i(\text{dc}) = V_{CC}I_{\text{dc}} = (25 \text{ V})(2.71 \text{ A}) = \mathbf{67.75 \text{ W}}$$

The power dissipated by each output transistor is

$$P_Q = \frac{P_{2Q}}{2} = \frac{P_i - P_o}{2} = \frac{67.75 \text{ W} - 36.125 \text{ W}}{2} = \mathbf{15.8 \text{ W}}$$

The circuit efficiency (for the input of 12 V, rms) is then

$$\% \eta = \frac{P_o}{P_i} \times 100\% = \frac{36.125 \text{ W}}{67.75 \text{ W}} \times 100\% = \mathbf{53.3\%}$$

#### EXAMPLE 15.11

For the circuit of Fig. 15.19, calculate the maximum input power, maximum output power, input voltage for maximum power operation, and the power dissipated by the output transistors at this voltage.

#### Solution

The maximum input power is

$$\text{maximum } P_i(\text{dc}) = \frac{2V_{CC}^2}{\pi R_L} = \frac{2(25 \text{ V})^2}{\pi 4 \Omega} = \mathbf{99.47 \text{ W}}$$

The maximum output power is

$$\text{maximum } P_o(\text{ac}) = \frac{V_{CC}^2}{2R_L} = \frac{(25 \text{ V})^2}{2(4 \Omega)} = \mathbf{78.125 \text{ W}}$$

[Note that the maximum efficiency is achieved:]

$$\% \eta = \frac{P_o}{P_i} \times 100\% = \frac{78.125 \text{ W}}{99.47 \text{ W}} 100\% = \mathbf{78.54\%}$$

To achieve maximum power operation the output voltage must be

$$V_L(\text{p}) = V_{CC} = \mathbf{25 \text{ V}}$$

and the power dissipated by the output transistors is then

$$P_{2Q} = P_i - P_o = 99.47 \text{ W} - 78.125 \text{ W} = \mathbf{21.3 \text{ W}}$$

#### EXAMPLE 15.12

For the circuit of Fig. 15.19, determine the maximum power dissipated by the output transistors and the input voltage at which this occurs.

#### Solution

The maximum power dissipated by both output transistors is



$$\text{maximum } P_{2Q} = \frac{2V_{CC}^2}{\pi^2 R_L} = \frac{2(25 \text{ V})^2}{\pi^2 4 \Omega} = \mathbf{31.66 \text{ W}}$$

This maximum dissipation occurs at

$$V_L = 0.636V_{L(p)} = 0.636(25 \text{ V}) = \mathbf{15.9 \text{ V}}$$

(Notice that at  $V_L = 15.9 \text{ V}$  the circuit required the output transistors to dissipate  $31.66 \text{ W}$ , while at  $V_L = 25 \text{ V}$  they only had to dissipate  $21.3 \text{ W}$ .)

## 15.6 AMPLIFIER DISTORTION

A pure sinusoidal signal has a single frequency at which the voltage varies positive and negative by equal amounts. Any signal varying over less than the full  $360^\circ$  cycle considered to have distortion. An ideal amplifier is capable of amplifying a pure sinusoidal signal to provide a larger version, the resulting waveform being a pure single-frequency sinusoidal signal. When distortion occurs the output will not be an exact duplicate (except for magnitude) of the input signal.

Distortion can occur because the device characteristic is not linear, in which case nonlinear or amplitude distortion occurs. This can occur with all classes of amplifier operation. Distortion can also occur because the circuit elements and devices respond to the input signal differently at various frequencies, this being frequency distortion. One technique for describing distorted but periodic waveforms uses Fourier analysis, a method that describes any periodic waveform in terms of its fundamental frequency component and frequency components at integer multiples—these components are called **harmonic components or harmonics**. For example, a signal that is originally  $1000 \text{ Hz}$  could result, after distortion, in a frequency component at  $1000 \text{ Hz}$  ( $1 \text{ kHz}$ ) and harmonic components at  $2 \text{ kHz}$  ( $2 \times 1 \text{ kHz}$ ),  $3 \text{ kHz}$  ( $3 \times 1 \text{ kHz}$ ),  $4 \text{ kHz}$  ( $4 \times 1 \text{ kHz}$ ), and so on. The original frequency of  $1 \text{ kHz}$  is called the **fundamental frequency**; those at integer multiples are the harmonics. The  $2\text{-kHz}$  component is therefore called a second harmonic that at  $3 \text{ kHz}$  is the third harmonic, and so on. The fundamental frequency is not considered a harmonic. Fourier analysis does not allow for fractional harmonic frequencies—only integer multiples of the fundamental.

### Harmonic Distortion

A signal is considered to have harmonic distortion when there are harmonic frequency components (not just the fundamental component). If the fundamental frequency has an amplitude,  $A_1$ , and the  $n$ th frequency component has an amplitude,  $A_n$ , a harmonic distortion can be defined as

$$\% \text{ } n\text{th harmonic distortion} = \% D_n = \frac{|A_n|}{|A_1|} \times 100\% \quad (15.30)$$

The fundamental component is typically larger than any harmonic component.

**EXAMPLE 15.13**

Calculate the harmonic distortion components for an output signal having fundamental amplitude of 2.5 V, second harmonic amplitude of 0.25 V, third harmonic amplitude of 0.1 V, and fourth harmonic amplitude of 0.05 V.

**Solution**

Using Eq. (15.30) yields

$$\% D_2 = \frac{|A_2|}{|A_1|} \times 100\% = \frac{0.25 \text{ V}}{2.5 \text{ V}} \times 100\% = 10\%$$

$$\% D_3 = \frac{|A_3|}{|A_1|} \times 100\% = \frac{0.1 \text{ V}}{2.5 \text{ V}} \times 100\% = 4\%$$

$$\% D_4 = \frac{|A_4|}{|A_1|} \times 100\% = \frac{0.05 \text{ V}}{2.5 \text{ V}} \times 100\% = 2\%$$

**TOTAL HARMONIC DISTORTION**

When an output signal has a number of individual harmonic distortion components, the signal can be seen to have a total harmonic distortion based on the individual elements as combined by the relationship of the following equation:

$$\% \text{ THD} = \sqrt{D_2^2 + D_3^2 + D_4^2 + \cdots} \times 100\% \quad (15.31)$$

Where **THD** is total harmonic distortion

**EXAMPLE 15.14**

Calculate the total harmonic distortion for the amplitude components given in Example 15.13.

**Solution**

Using the computed values of  $D_2 = 0.10$ ,  $D_3 = 0.04$ , and  $D_4 = 0.02$  in Eq. (15.31),

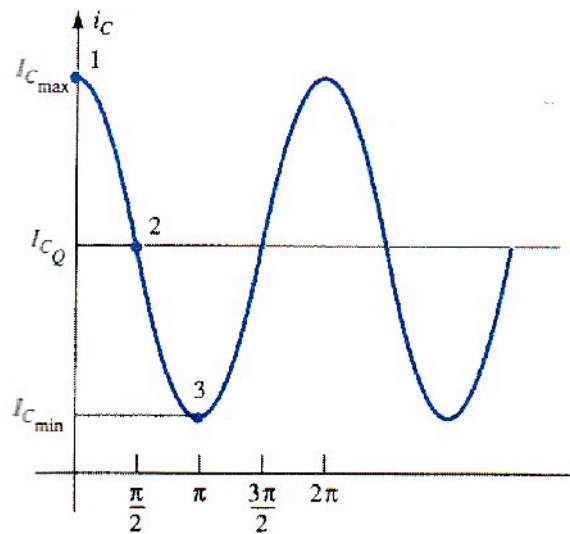
$$\begin{aligned} \% \text{ THD} &= \sqrt{D_2^2 + D_3^2 + D_4^2} \times 100\% \\ &= \sqrt{(0.10)^2 + (0.04)^2 + (0.02)^2} \times 100\% = 0.1095 \times 100\% \\ &= 10.95\% \end{aligned}$$

An instrument such as a spectrum analyzer would allow measurement of the harmonics present in the signal by providing a display of the fundamental component of a signal and a number of its harmonics on a display screen. Similarly, a wave analyzer instrument allows more precise measurement of the harmonic components of a distorted signal by filtering out each of these components and providing a reading of these components. In any case, the technique of considering any distorted signal as containing a fundamental component and harmonic components is practical

and useful. For a signal occurring in class AB or class B, the distortion may be mainly even harmonics, of which the second harmonic component is the largest. Thus, although the distorted signal theoretically contains all harmonic components from the second harmonic up. The most important in terms of the amount of distortion in the classes presented above is the second harmonic.

### SECOND HARMONIC DISTORTION

Figure 15.20 shows a waveform to use for obtaining second harmonic distortion. A collector current waveform is shown with the quiescent, minimum, and maximum signal levels, and the time at which they occur is marked on the waveform.



**Fig 15.20 Waveform for obtaining second harmonic distortion**

The signal shown indicates that some distortion is present. An equation that approximately describes the distorted signal waveform is

$$i_C \approx I_{C_Q} + I_0 + I_1 \cos \omega t + I_2 \cos 2\omega t \quad (15.32)$$

The current waveform contains the original quiescent current  $I_{C_Q}$ , which occurs with zero input signal; an additional dc current  $I_0$ , due to the nonzero average of the distorted signal the fundamental component of the distorted ac signal,  $I_1$ ; and a second harmonic component  $I_2$ , at twice the fundamental frequency. Although other harmonics, are also present, only the second is considered here. Equating the resulting current from Eq. (15.32) at a few points in the cycle to that shown on the current waveform provides the following three relations:

At point 1 ( $\omega t = 0$ ):

$$i_C = I_{C_{\max}} = I_{C_Q} + I_0 + I_1 \cos 0 + I_2 \cos 0$$

$$I_{C_{\max}} = I_{C_Q} + I_0 + I_1 + I_2$$

At point 2 ( $\omega t = \pi/2$ ):

$$i_C = I_{C_Q} = I_{C_Q} + I_0 + I_1 \cos \frac{\pi}{2} + I_2 \cos \frac{2\pi}{2}$$

$$I_{C_Q} = I_{C_Q} + I_0 - I_2$$

At point 3 ( $\omega t = \pi$ ):

$$i_C = I_{C_{min}} = I_{C_Q} + I_0 + I_1 \cos \pi + I_2 \cos 2\pi$$

$$I_{C_{min}} = I_{C_Q} + I_0 - I_1 + I_2$$

Solving the preceding three equations simultaneously gives the following results:

$$I_0 = I_2 = \frac{I_{C_{max}} + I_{C_{min}} - 2I_{C_Q}}{4}, \quad I_1 = \frac{I_{C_{max}} - I_{C_{min}}}{2}$$

Referring to Eq. (15.30), the definition of second harmonic distortion may be expressed as

$$D_2 = \left| \frac{I_2}{I_1} \right| \times 100\%$$

Inserting the values of  $I_1$  and  $I_2$  determined above gives

$$D_2 = \left| \frac{\frac{1}{2}(I_{C_{max}} + I_{C_{min}}) - I_{C_Q}}{I_{C_{max}} - I_{C_{min}}} \right| \times 100\% \quad (15.33)$$

In a similar manner, the second harmonic distortion can be expressed in terms of measured collector-emitter voltages:

$$D_2 = \left| \frac{\frac{1}{2}(V_{CE_{max}} + V_{CE_{min}}) - V_{CE_Q}}{V_{CE_{max}} - V_{CE_{min}}} \right| \times 100\% \quad (15.34)$$

### EXAMPLE 15.5

Calculate the second harmonic distortion, if an output waveform displayed on an oscilloscope provides the following measurements:

(a)  $V_{CE_{min}} = 1 \text{ V}$ ,  $V_{CE_{max}} = 22 \text{ V}$ ,  $V_{CE_Q} = 12 \text{ V}$ .

(b)  $V_{CE_{min}} = 4 \text{ V}$ ,  $V_{CE_{max}} = 20 \text{ V}$ ,  $V_{CE_Q} = 12 \text{ V}$ .

**Solution**

Using Eq. (15.34), we get

$$(a) D_2 = \left| \frac{\frac{1}{2}(22 \text{ V} + 1 \text{ V}) - 12 \text{ V}}{22 \text{ V} - 1 \text{ V}} \right| \times 100\% = \mathbf{2.38\%}$$

$$(b) D_2 = \left| \frac{\frac{1}{2}(20 \text{ V} + 4 \text{ V}) - 12 \text{ V}}{20 \text{ V} - 4 \text{ V}} \right| \times 100\% = \mathbf{0\%} \quad (\text{no distortion})$$

### Power of Signal Having Distortion

When distortion does occur, the output power calculated for the undistorted signal is no longer correct. When distortion is present, the output power delivered to the load resistor  $R_C$  due to the fundamental component of the distorted signal is

$$P_1 = \frac{I_1^2 R_C}{2} \quad (15.35)$$

The total power due to all the harmonic components of the distorted signal can then be calculated using

$$P = (I_1^2 + I_2^2 + I_3^2 + \cdots) \frac{R_C}{2} \quad (15.36)$$

The total power can also be expressed in terms of the total harmonic distortion

$$P = (1 + D_2^2 + D_3^2 + \cdots) I_1^2 \frac{R_C}{2} = (1 + \text{THD}^2) P_1 \quad (15.37)$$

### EXAMPLE 15.16

For the harmonic distortion reading of  $D_2 = 0.1$ ,  $D_3 = 0.02$ , and  $D_4 = 0.01$ , with  $I_1 = 4 \text{ A}$  and  $R_C = 8 \Omega$ , calculate the total harmonic distortion, fundamental power component, and total power.

#### Solution

The total harmonic distortion is

$$\text{THD} = \sqrt{D_2^2 + D_3^2 + D_4^2} = \sqrt{(0.1)^2 + (0.02)^2 + (0.01)^2} \approx \mathbf{0.1}$$

The fundamental power, using Eq. (15.35), is

$$P_1 = \frac{I_1^2 R_C}{2} = \frac{(4 \text{ A})^2 (8 \Omega)}{2} = \mathbf{64 \text{ W}}$$

The total power calculated using Eq. (15.37) is then

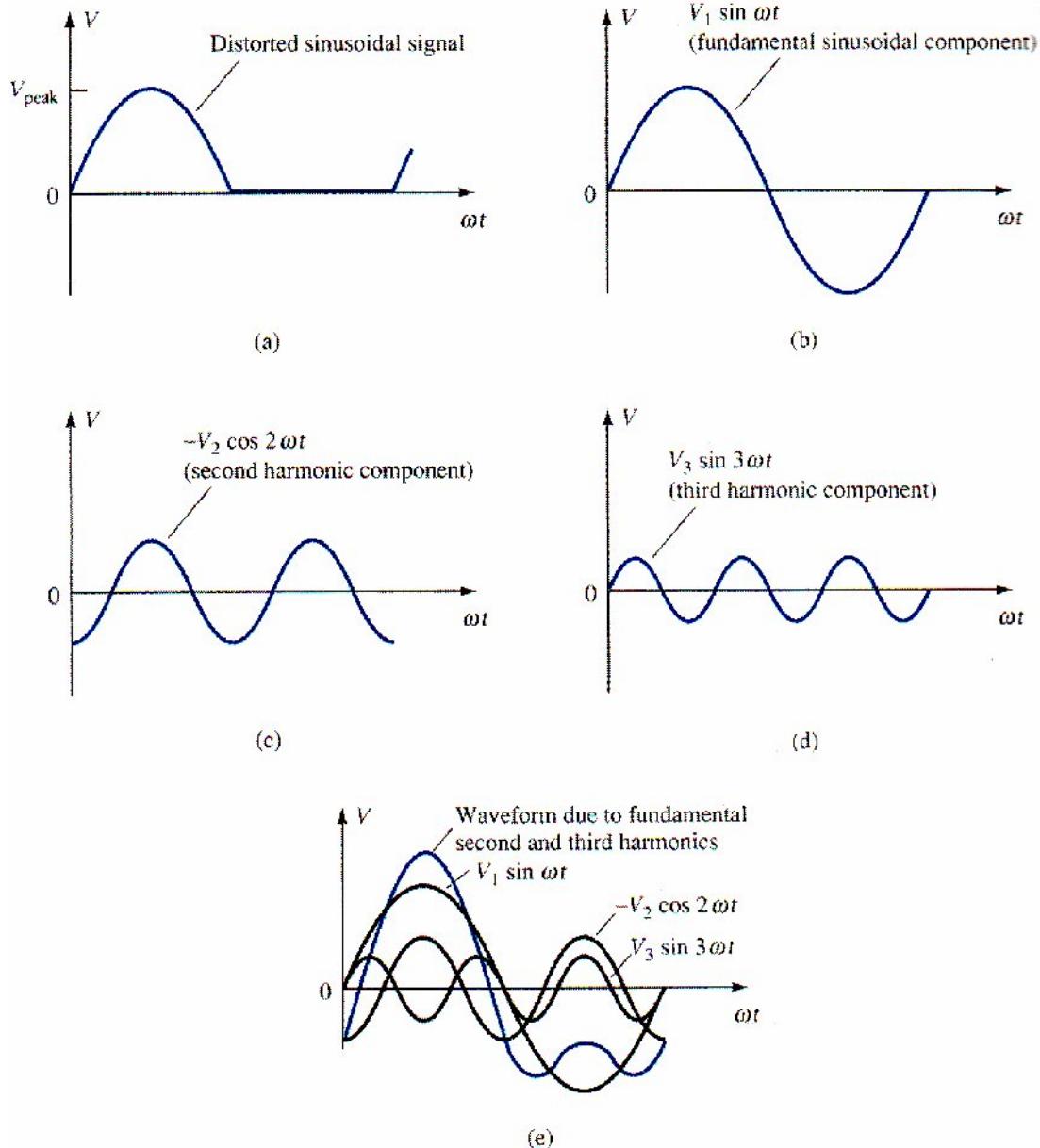
$$P = (1 + \text{THD}^2) P_1 = [1 + (0.1)^2] 64 = (1.01) 64 = \mathbf{64.64 \text{ W}}$$

(Note that the total power is due mainly to the fundamental component even with 10% second harmonic distortion.)



### Graphical Description of Harmonic Components of Distorted Signal

A distorted waveform such as that which occurs in class B operation can be represented using Fourier analysis as a fundamental with harmonic components. Figure 15.21a shows a positive half-cycle such as the type that would result in one side of a class B amplifier.



**Fig 15.21 Graphical representation of a distorted signal through the use of harmonic components**

Using Fourier analysis techniques, the fundamental component of the distorted signal can be obtained, as shown in Fig. 15.21 b. Similarly, the second and third harmonic components can be obtained and are shown in Fig. 15.21c and d, respectively. Using the Fourier technique, the distorted waveform can be made by adding the fundamental and harmonic components, as shown in Fig.

15.21 e. *In general, any periodic distorted waveform can be represented by adding a fundamental component and all harmonic components, each of varying amplitude and at various phase angles*