# Power amplifiers

## Classification of Power Amplifiers

Power amplifiers are generally classified into five types: A, B, AB, and C for analog designs and class D for switching designs. This classification is based on the percentage of the input cycle for which the amplifier operates in its **linear region**. The waveforms of the output currents for various types of amplifiers are shown in Fig. 1.

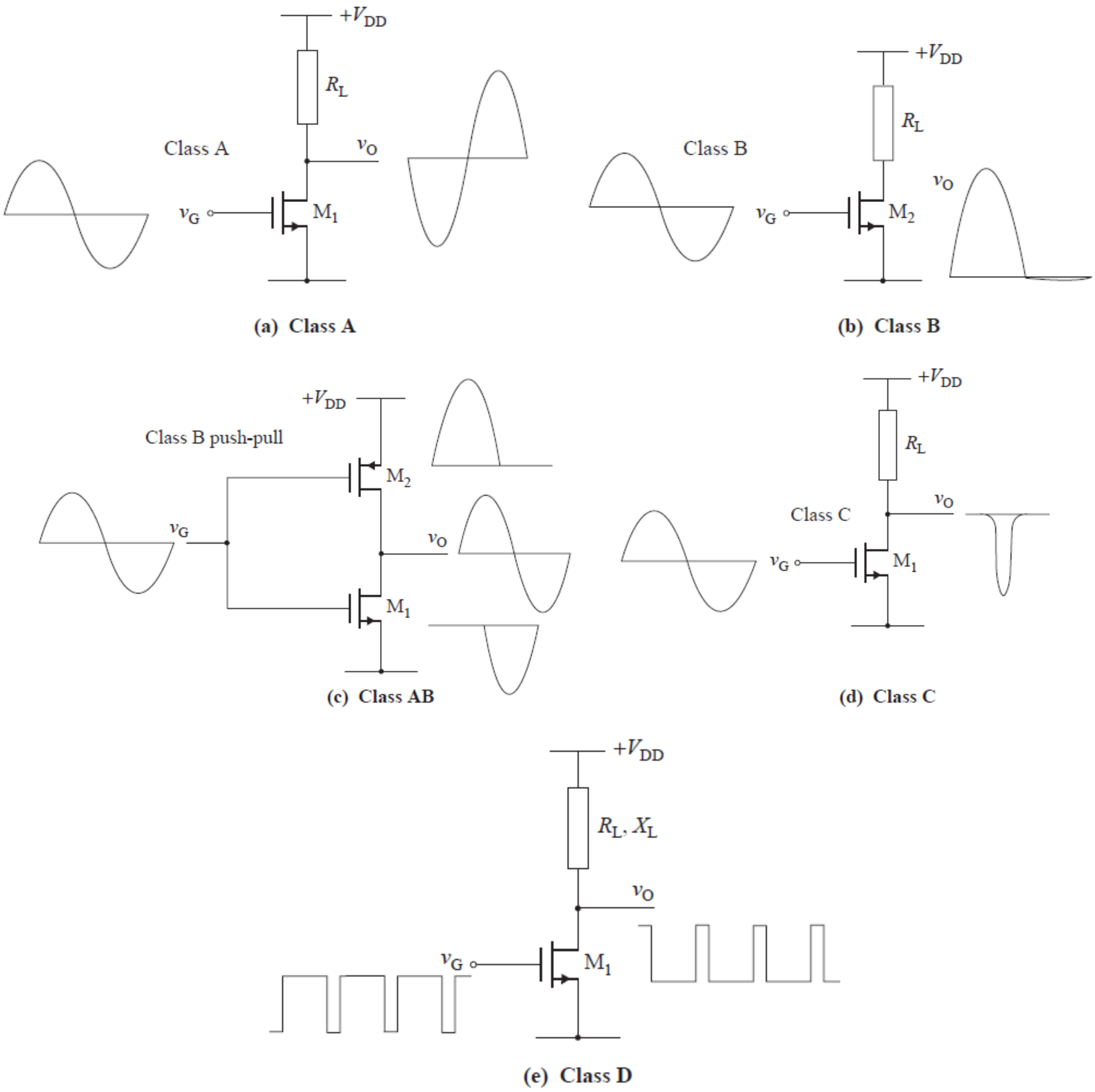


**FIGURE 1** Output voltages for various classes of amplifiers

An amplifier receives a signal from input source and provides a larger version of the signal to some output device or to another amplifier stage. An input signal is generally small (a few microvolts from an antenna) and needs to be amplified sufficiently to operate an output device (speaker or other power-handling device).

Power amplifiers primarily provide sufficient power to an output load to drive a speaker or other power device, typically a few watts to tens of watts.

The main features of a power 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.

**Amplifier Efficiency**

The power efficiency of an amplifier, defined as the ratio of power output to power input. In a class A amplifier, the maximum efficiency occurring for the largest output voltage and current swing (only 25% with a direct 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-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.

**TABLE 1**
*Comparison of Amplifier Classes*

| Class | A | AB | B | C | 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% |

## CLASS A AMPLIFIER

The simple circuit of a class A amplifier shown in Fig. 2. The signals handled by the 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. The 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**,

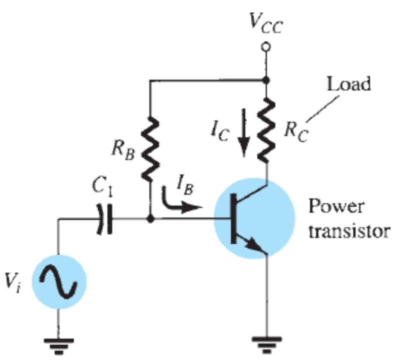


Fig. 2

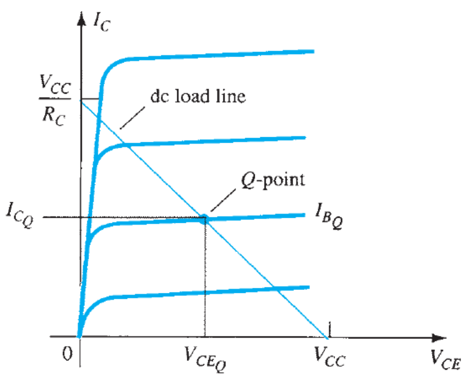


Fig. 3

## DC Bias Operation

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

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

with the collector current then being

$$I_C = \beta I_B$$

with the collector–emitter voltage then

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

To appreciate the importance of the dc bias on the operation of the power amplifier, consider the collector characteristic shown in Fig. 3 . **A dc 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. (1) through (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 ($Q$–point set at optimum bias point).**

## AC Operation

When an input ac signal is applied to the amplifier of Fig. 2, the output will vary from its dc bias operating voltage and current. A small input signal, as shown in Fig. 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, $V_{CC}$.**

## 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 $I_{CQ}$. The power then drawn from the supply is:

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

Even with an ac signal applied, the average current drawn from the supply remains equal to the quiescent current $I_{CQ}$, so that Eq.(4) represents the input power supplied to the class A amplifier.

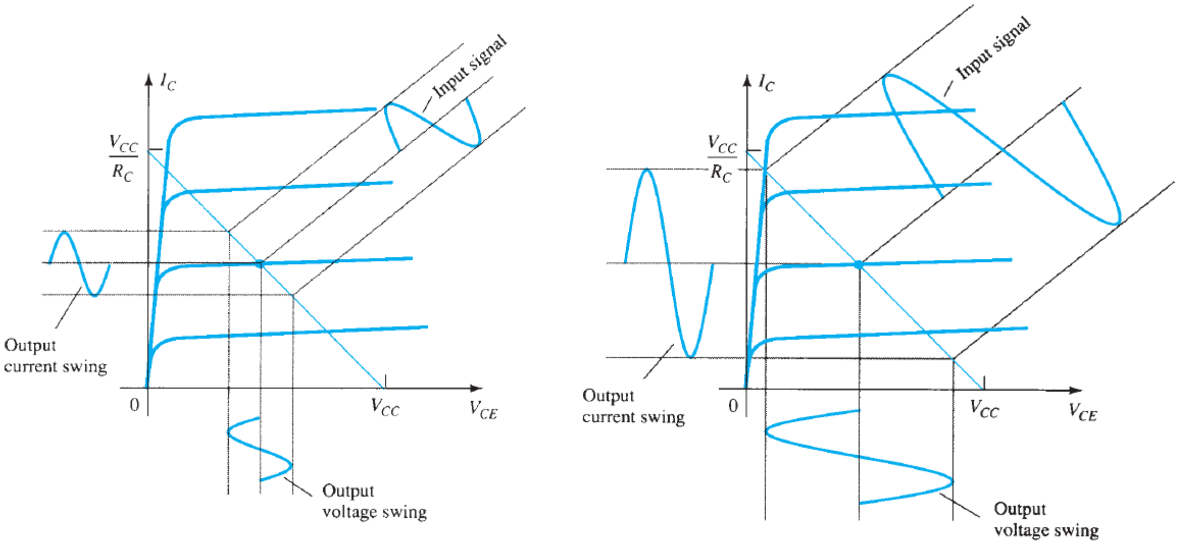


Fig. 4

## 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. 2. The ac signal $Vi$ 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. 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.

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

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

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

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

## 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

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

**Maximum Efficiency** = 25% (This maximum efficiency will occur only for ideal conditions of both voltage swing and current swing, most of class A circuits will provide efficiencies of much less than 25%.)

**EXAMPLE 1:** Calculate the input power, output power, and efficiency of the amplifier circuit in Fig. 5 for an input voltage that results in a base current of 10 mA peak.

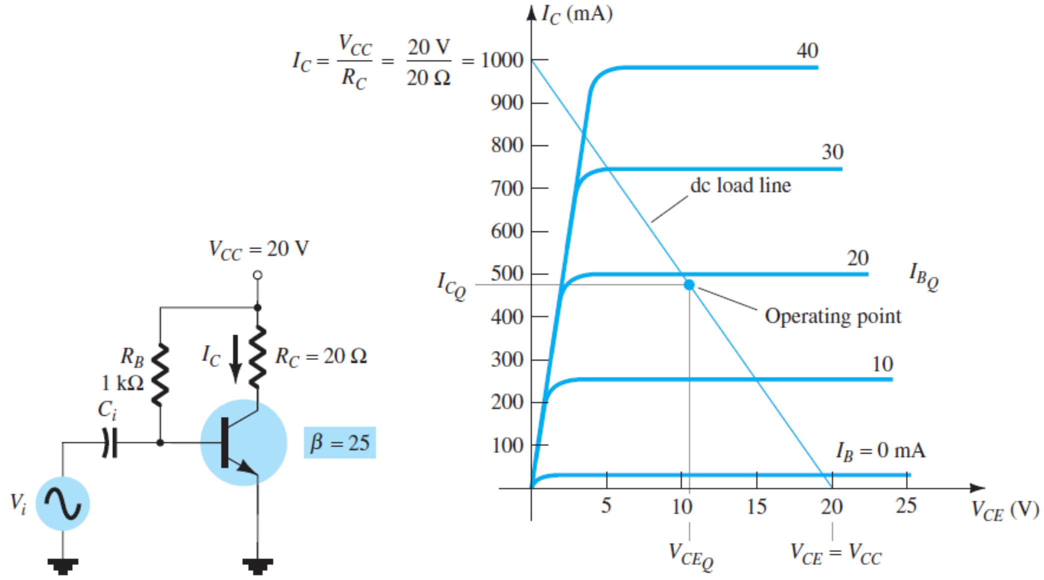


Fig.5

***Solution:***

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

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

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

$P_{dc} = I_{CQ} * V_{CC} = 0.48*20 = 9.6$Watt

The ac variation of the output signal can be obtained graphically using the dc load line drawn on Fig. 4- b by connecting $V_{CE} = V_{CC} = 20$ V with $I_C = V_{CC}/R_C = 1000$ mA $= 1$ A

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

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

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

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

## 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 a simple circuit of Fig. 6.

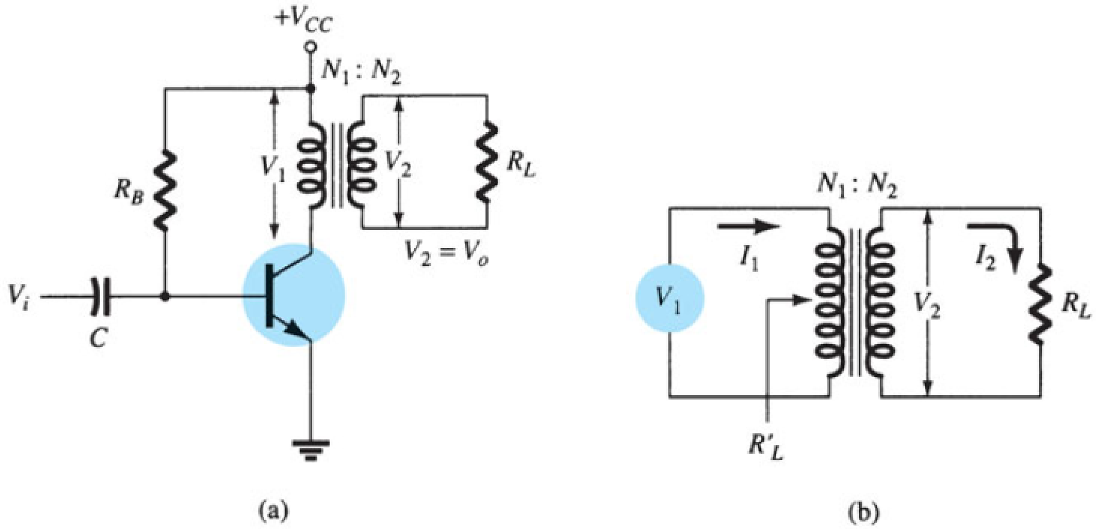


**FIG. 6** *Transformer-coupled audio power amplifier.*

### Transformer Action

A transformer can increase or decrease voltage or current levels according to the turns ratio. In the following discussion assumes ideal (100%) power transfer from primary to secondary, that is, no power losses are considered.

**Voltage Transformation:** The voltage transformation is given by

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

**Current Transformation**: The current transformation is given by

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

**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. 7- c, 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:

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

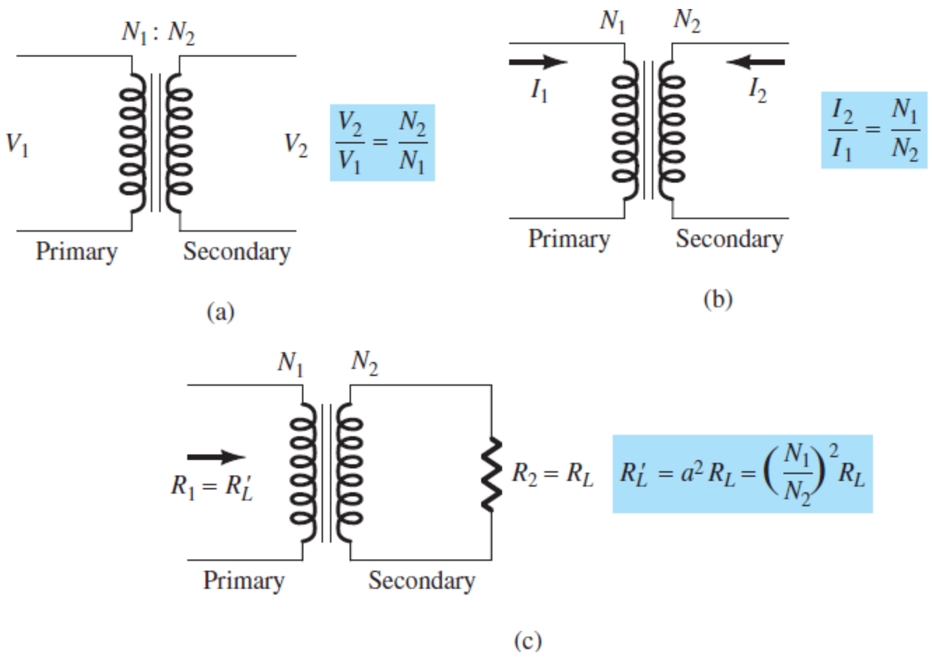


**FIG.7:** *(a) voltage transformation; (b) current transformation;(c) impedance transformation.*

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

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

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

$$R_1 = a^2 R_2 \quad \text{or} \quad R_L' = a^2 R_L$$

where $R'_L$ is the reflected impedance. As shown in Eq. , 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 2:** What transformer turns ratio is required to match a 16Ω speaker load so that the effective load resistance seen at the primary is 10 kΩ.

***Solution:***

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

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

# Operation of Amplifier Stage

## DC Load Line

**The transformer (dc) winding resistance determines the dc load line** for the circuit of Fig. 6. **Typically, this dc resistance is small (ideally 0Ω).** In Fig. 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 0Ω dc load resistance, and the load line is drawn straight vertically from the voltage point, $V_{CEQ} = V_{CC}$.**

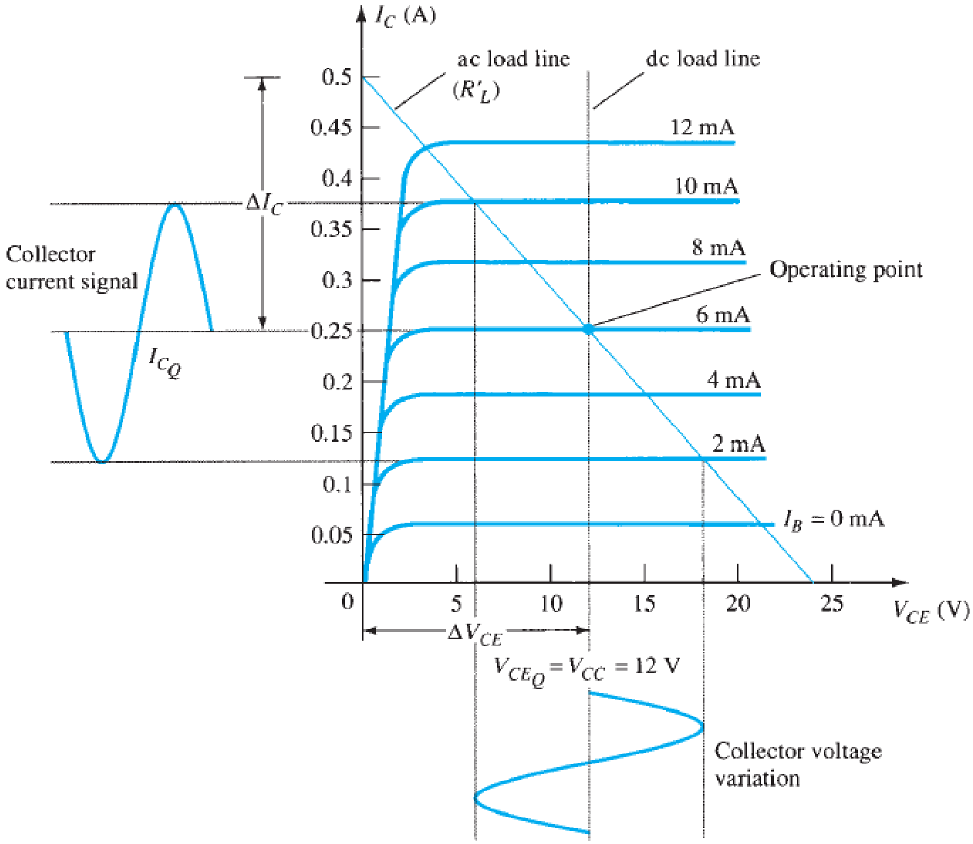


**FIG. 8:** *Load lines for class A transformer-coupled amplifier.*

## Quiescent Operating Point

**The operating point in the characteristic curve of Fig. 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 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.11 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 9 shows the voltage and current signal swings from the circuit of Fig. 6 . From the signal variations shown in Fig. 8 , the values of the peak-to-peak signal swings are:

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

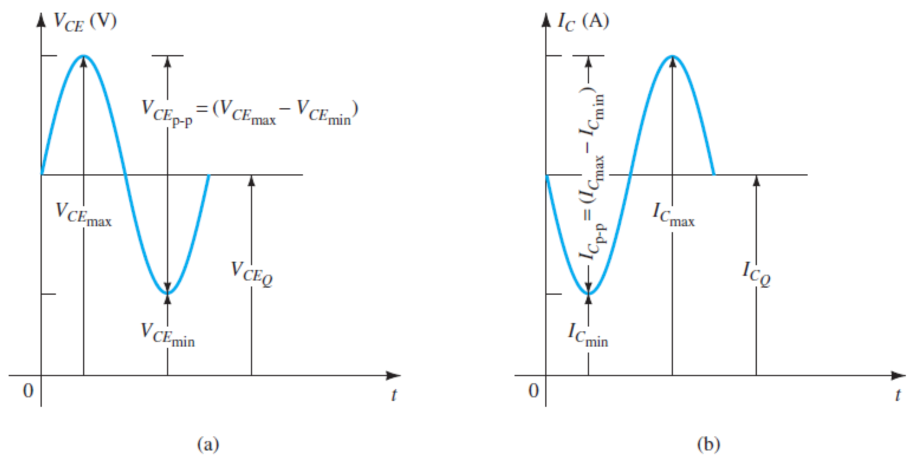


**FIG. 9:** *Graphical operation of transformer-coupled class A amplifier.*

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

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

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. (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. (7):

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

The power across the load can then be expressed as

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

Using Eq. (8) 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

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

**Efficiency**

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

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

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

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

**where $P_Q$ is the power dissipated as heat**. 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 3:** Calculate the ac power delivered to the 8Ω speaker for the circuit of Fig. 10. The circuit component values result in a dc base current of 6 mA, and the input signal (*Vi*) results in a peak base current swing of 4 mA.

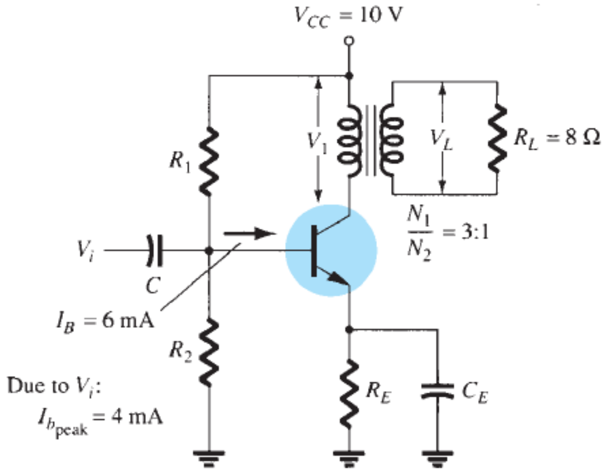


**FIG. 10:** *Transformer-coupled class A amplifier*

***Solution:*** The dc load line is drawn vertically (see Fig. 11 ) from the voltage point:

$V_{CEQ} = V_{CC} = 10$ V

For $I_B = 6$ mA, the operating point on Fig. 10 is $V_{CEQ} = 10$ V and $I_{CQ} = 140$ 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* :

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

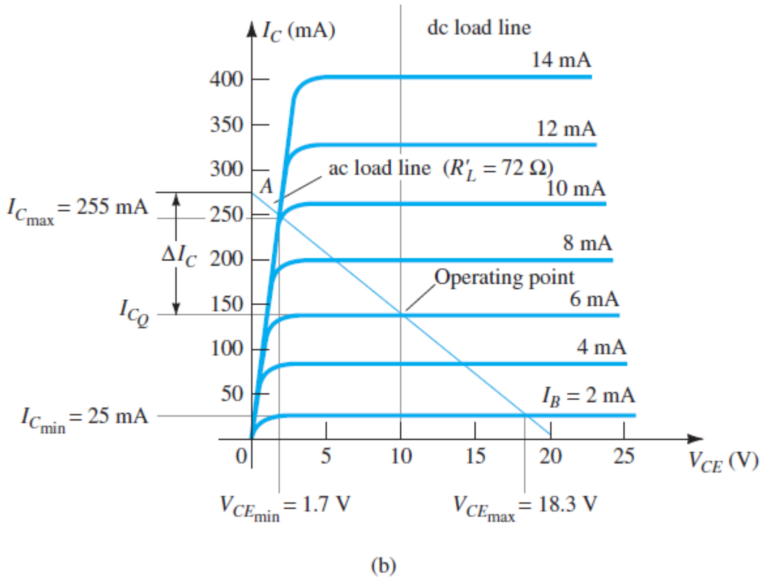


**FIG. 11:** *Transformer-coupled class A transistor characteristic for Examples 3 and 4 : (a) device characteristic; (b) dc and ac load lines.*

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. 10 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

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

**EXAMPLE 4:** For the circuit of Fig. 10 and results of Example 3 , calculate the dc input power, power dissipated by the transistor, and efficiency of the circuit for the input signal of Example 3.

***Solution:***

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

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

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%.

**EXAMPLE 5:** 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 $V_{CEQ} = V_{CC} = 12$ 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.

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

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

resulting in

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

c.

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

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

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 $V_{(p)} = V_{CC}$ to slightly over 1% for $V_{(p)} = 2$ V.

# CLASS B AMPLIFIER OPERATION

In class B, the transistor turning on when the ac signal is applied. 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 11 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 class B operation of these transistors provides greater efficiency than was possible using a single transistor in class A operation.

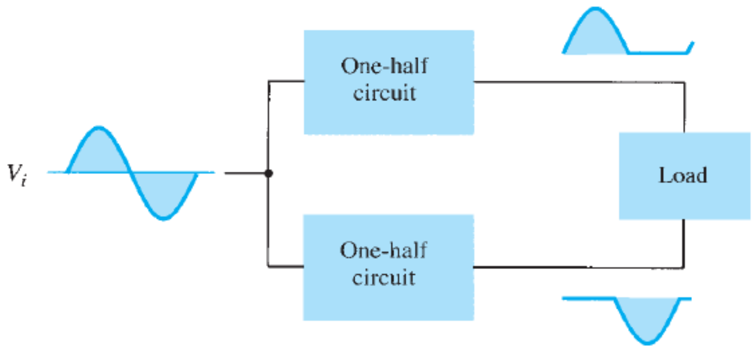


FIG. 11:*Block representation of push–pull operation.*

**Input (DC) Power**

The power supplied to the load by an amplifier is drawn from the power supply (see Fig. 12) that provides the input (or dc power). The amount of this input power can be calculated using:

$$P_i(\mathrm{dc}) = V_{CC} I_{\mathrm{dc}} \qquad (1)$$

where $I_{dc}$ is the average or dc current drawn from the power supplies. The value of the average current drawn can be expressed as

$$I_{\mathrm{dc}} = \frac{2}{\pi} I(\mathrm{p}) \qquad (2)$$

where $I_{(p)}$ is the peak value of the output current waveform. Using Eq. (2) in the power input equation (1) results in

$$P_i(\mathrm{dc}) = V_{CC}\left(\frac{2}{\pi} I(\mathrm{p})\right) \qquad (3)$$

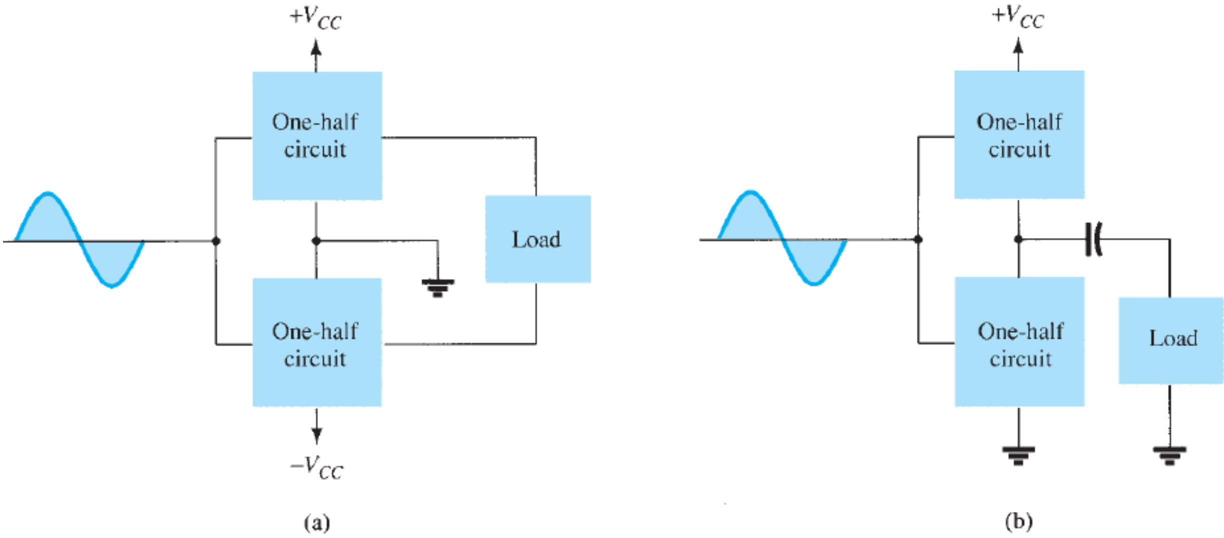


**FIG.12:***Connection of push–pull amplifier to load: (a) using two voltage supplies; (b) using one voltage supply.*

## Output (AC) Power

The power delivered to the load (usually referred to as a resistance $R_L$ ) can be calculated using any one of the following equations:

If one is using an rms meter to measure the voltage across the load, the output power can be calculated as:

$$P_o(\text{ac}) = \frac{V_L^2(\text{rms})}{R_L} \quad (4)$$

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

$$P_o(\text{ac}) = \frac{V_L^2(\text{p-p})}{8R_L} = \frac{V_L^2(\text{p})}{2R_L} \quad (5)$$

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

$$\%\,\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% \quad (6)$$

Using Eqs. (3) and (5) in the efficiency equation above results in

$$\%\,\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\% = \frac{V_L^2(\text{p})/2R_L}{V_{CC}[(2/\pi)I(\text{p})]} \times 100\% = \frac{\pi}{4}\,\frac{V_L(\text{p})}{V_{CC}} \times 100\% \quad (7)$$

[using $I_{(\text{p})} = V_{L(\text{p})}/R_L$ ]. Equation (7) shows that the larger the peak voltage, the higher is the circuit efficiency, up to a maximum value when $V_{L(\text{p})} = VCC$, this maximum efficiency then being

$$\text{maximum efficiency} = \frac{\pi}{4} \times 100\% = 78.5\% \qquad (8)$$

**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,

$$P_{2Q} = P_{i(\mathrm{dc})} - P_{o(\mathrm{ac})} \qquad \textbf{(9)}$$

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

$$PQ = P_{2Q} / 2 \qquad (10)$$

**EXAMPLE 6:** For a class B amplifier providing a 20-V peak signal to a 16Ω 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

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

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

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

and the input power delivered by the supply voltage is

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

The output power delivered to the load is

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

for a resulting efficiency of

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

**Maximum Power Considerations**

For class B operation, the maximum output power is delivered to the load when

$$V_{L(\mathrm{p})} = V_{CC} \qquad (11)$$

$$\text{maximum } P_o(\mathrm{ac}) = \frac{V_{CC}^2}{2R_L} \qquad (12)$$

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

$$I(\mathrm{p}) = \frac{V_{CC}}{R_L} \quad (13)$$

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

$$\text{maximum } I_{dc} = \frac{2}{\pi} I(\mathrm{p}) = \frac{2V_{CC}}{\pi R_L} \quad (14)$$

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

$$\text{maximum } P_i(\mathrm{dc}) = V_{CC}(\text{maximum } I_{dc}) = V_{CC}\left(\frac{2V_{CC}}{\pi R_L}\right) = \frac{2V_{CC}^2}{\pi R_L} \quad (15)$$

The maximum circuit efficiency for class B operation is then

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

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

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**

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

for a maximum transistor power dissipation of

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

**EXAMPLE 7:** For a class B amplifier using a supply of $V_{CC} = 30$ V and driving a load of 16Ω, determine the maximum input power, output power, and transistor dissipation.

**Solution:** The maximum output power is

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

The maximum input power drawn from the voltage supply is

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

The circuit efficiency is then

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

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

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

**EXAMPLE 8:** Calculate the efficiency of a class B amplifier for a supply voltage of $V_{CC} = 24\text{V}$ with peak output voltages of: a. $V_{L(\text{p})} = 22$ V. b. $V_{L(\text{p})} = 6$ V.

***Solution:***

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

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

Notice that a voltage near the maximum [22V in part (a)] results in an efficiency near the maximum, whereas a small voltage swing [6V 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.

## CLASS B AMPLIFIER CIRCUITS

A number of circuit arrangements for obtaining class B operation are possible. There are two common approaches for using push-pull amplifiers to reproduce the entire waveform. The first approach uses transformer coupling. The second uses two **complementary symmetry transistors** (*npn* and *pnp* , or *n*MOS and *p*MOS).

### 1- Transformer-Coupled Push–Pull Circuits

Transformer coupling is illustrated in Figure 13. The input transformer has a center-tapped secondary that is connected to ground, producing phase inversion of one side with respect to the other. The input transformer thus converts the input signal to two out-of-phase signals for the transistors. Notice that both transistors are *npn* types. Because of the signal inversion, *Q*1 will conduct on the positive part of the cycle and *Q*2 will conduct on the negative part. The overall signal developed across the load then varies over the full cycle of signal operation. The positive power supply signal is connected to the center tap of the output transformer.

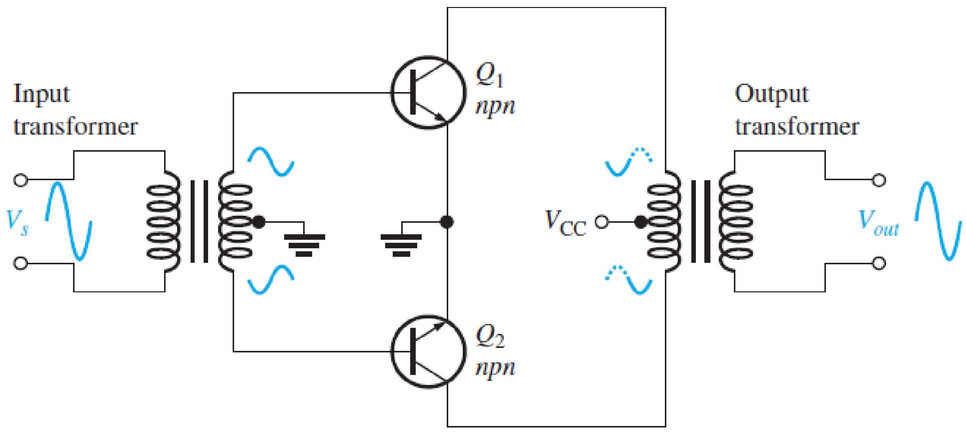


**FIG. 13:** *Transformer-coupled push-pull amplifiers. Q1 conducts during the positive half-cycle; Q2 conducts during the negative half-cycle. The two halves are combined by the output transformer.*

## 2- Complementary-Symmetry Circuits

Using complementary transistors ( *npn* and *pnp* ) it is possible to obtain a full cycle output across a load using half-cycles of operation from each transistor, as shown in Fig. 14-a. Whereas 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. 14-b. During the negative half-cycle of signal, the *pnp* transistor is biased into conduction when the input goes negative, as shown in Fig. 14-c. During a complete cycle of the input, a complete cycle of output signal is developed across the load.

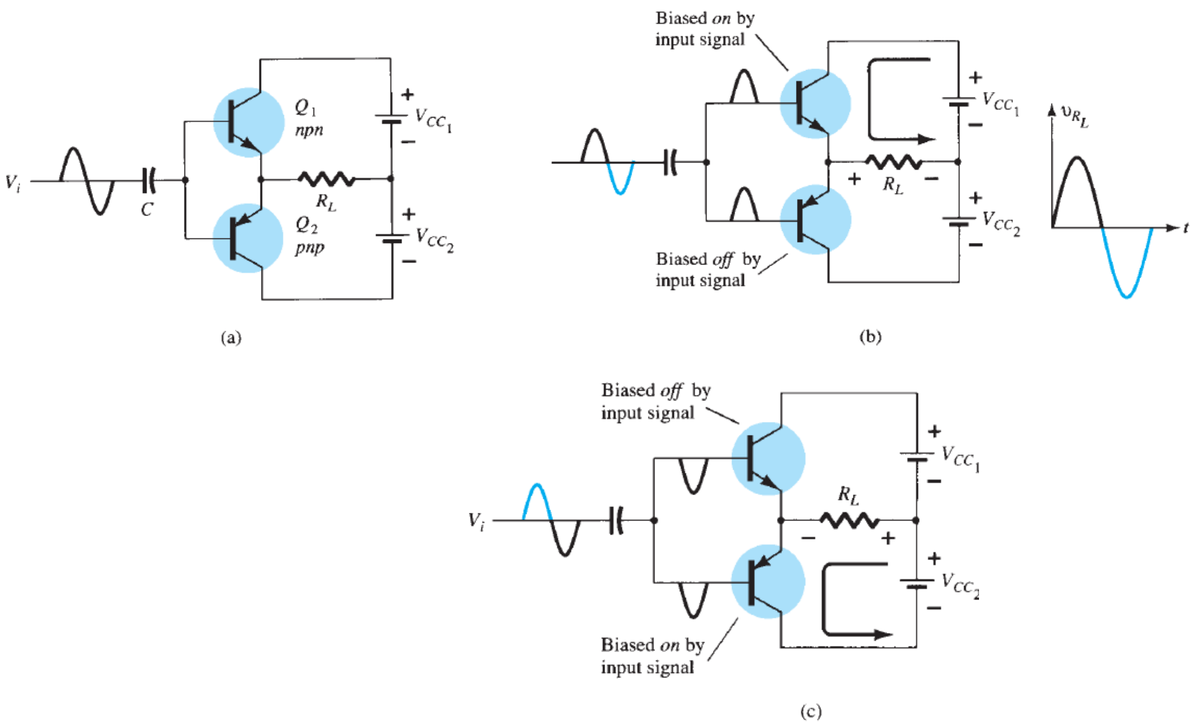


FIG. 14: *Complementary-symmetry push–pull circuit.*

## Crossover Distortion

When the dc base voltage is zero, both transistors are off and the input signal voltage must exceed $V_{BE}$ before a transistor conducts. Because of this, there is a time interval between the positive and negative alternations of the input when neither transistor is conducting, as shown in Figure 15. The resulting distortion in the output waveform is called **crossover distortion.** Biasing the transistors in class AB improves this operation by biasing both transistors to be on for more than half a cycle.

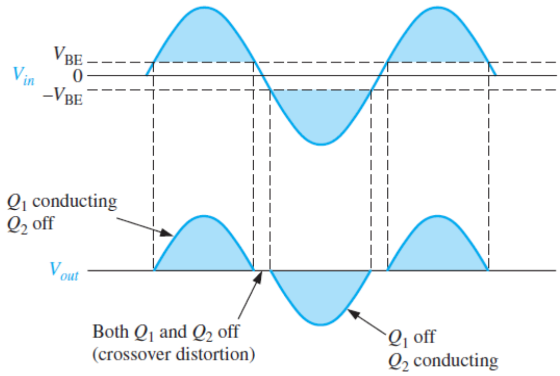


**FIG.15:** Illustration of crossover distortion in a class B push-pull amplifier. The transistors conduct only during portions of the input indicated by the shaded areas.

## Biasing the Push-Pull Amplifier for Class AB Operation

To overcome crossover distortion, the biasing is adjusted to just overcome the $V_{BE}$ of the transistors; this results in a modified form of operation called **class AB**. In class AB operation, the push-pull stages are biased into slight conduction, even when no input signal is present. This can be done with a voltage-divider and diode arrangement, as shown in Figure 16. When the diode characteristics of $D1$ and $D2$ are closely matched to the characteristics of the transistor base-emitter junctions, the current in the diodes and the current in the transistors are the same; this is called a **current mirror.** This current mirror produces the desired class AB operation and eliminates crossover distortion.

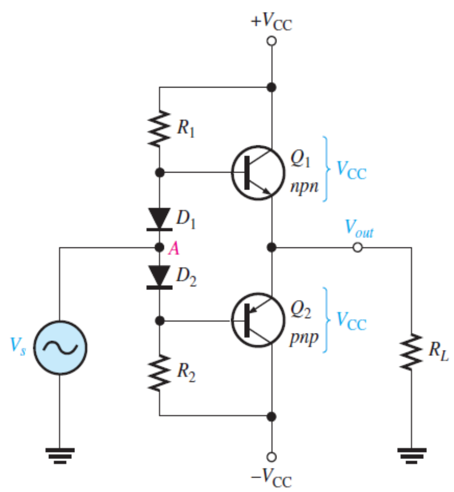


Fig. 16

In the bias path of the circuit in Figure 16, $R1$ and $R2$ are of equal value, as are the positive and negative supply voltages. This forces the voltage at point $A$ (between the diodes) to equal 0 V and eliminates the need for an input coupling capacitor. The dc voltage on the output is also 0V. Assuming that both diodes and both complementary transistors are identical, the drop across $D1$ equals the $V_{BE}$ of $Q1$, and the drop across $D2$ equals the $V_{BE}$ of $Q2$.

**EXAMPLE 9:** For the circuit of Fig. 17 , calculate the input power, output power, power handled by each output transistor and the circuit efficiency for an input of 12 V rms.(assume voltage gain unity)

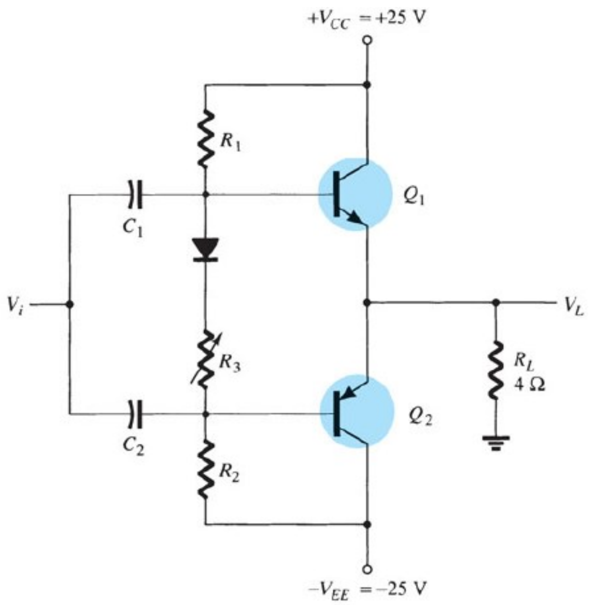


**FIG. 17:** *Class B power amplifier for Examples 9 to 11 .*

**Solution:** The peak input voltage is

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

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

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

and the output power developed across the load is

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

The peak load current is

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

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

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

so that the power supplied to the circuit is

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

The power dissipated by each output transistor is

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

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 10:** For the circuit of Fig. 17 , calculate the maximum input power, maximum output power, input voltage for maximum power operation, and power dissipated by the output transistors at this voltage.

**Solution:** The maximum input power is

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

The maximum output power is

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

[Note that the maximum efficiency is achieved:

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

To achieve maximum power operation the output voltage must be

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

and the power dissipated by the output transistors is then

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

**EXAMPLE 11:** For the circuit of Fig. 17 , 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

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

This maximum dissipation occurs at

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

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

## 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° cycle is 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 period 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 Hz could result, after distortion, in a frequency component at 1000Hz (1 kHz) and harmonic components at 2 kHz (2*1 kHz), 3kHz (3*1 kHz), 4 kHz (4*1kHz), and so on. The original frequency of 1 kHz is called the *fundamental frequency* ; those at integer multiples are the *harmonics* . The 2-kHz component is therefore called a *second harmonic* , that at 3 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

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

The fundamental component is typically larger than any harmonic component.

**EXAMPLE 12:** 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:**

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

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

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

**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:

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

where THD is total harmonic distortion.

**EXAMPLE 13:** Calculate the total harmonic distortion for the amplitude components given in Example 12.

**Solution:** Using the computed values of $D_2 = 0.10, D_3 = 0.04$, and $D_4 = 0.02$

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

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.

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

# CLASS C AND CLASS D AMPLIFIERS

Although class A, class AB, and class B amplifiers are most used as power amplifiers, class D amplifiers are popular because of their very high efficiency. Class C amplifiers, although not used as audio amplifiers, do find use in tuned circuits as in communications.

## Class C Amplifier

A class C amplifier, such as that shown in Fig. 18, is biased to operate for less than 180° of the input signal cycle. The tuned circuit in the output, however, will provide a full cycle of output signal for the fundamental or resonant frequency of the tuned circuit ( $L$ and $C$ tank circuit) of the output. This type of operation is therefore limited to use at one fixed frequency, as occurs in a communications circuit, for example. Operation of a class C circuit is not intended primarily for large-signal or power amplifiers.

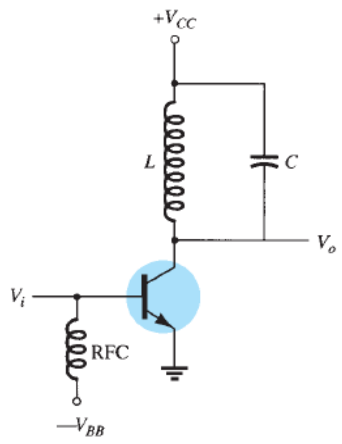


**FIG. 18:** *Class C amplifier circuit.*

## Class D Amplifier

A class D amplifier is designed to operate with digital or pulse-type signals. An efficiency of over 90% is achieved using this type of circuit, making it quite desirable in power amplifiers. It is necessary, however, to convert any input signal into a pulse-type waveform before using it to drive a large power load and to convert the signal back into a sinusoidal type signal to recover the original signal. Fig. 19 shows how a sinusoidal signal may be converted into a pulse-type signal using some form of sawtooth or chopping waveform to be applied with the input into a comparator-type op-amp circuit so that a representative pulse-type signal is produced. Although the letter D is used to describe the next type of bias operation after class C, the D could also be considered to stand for "Digital," since that is the nature of the signals provided to the class D amplifier.

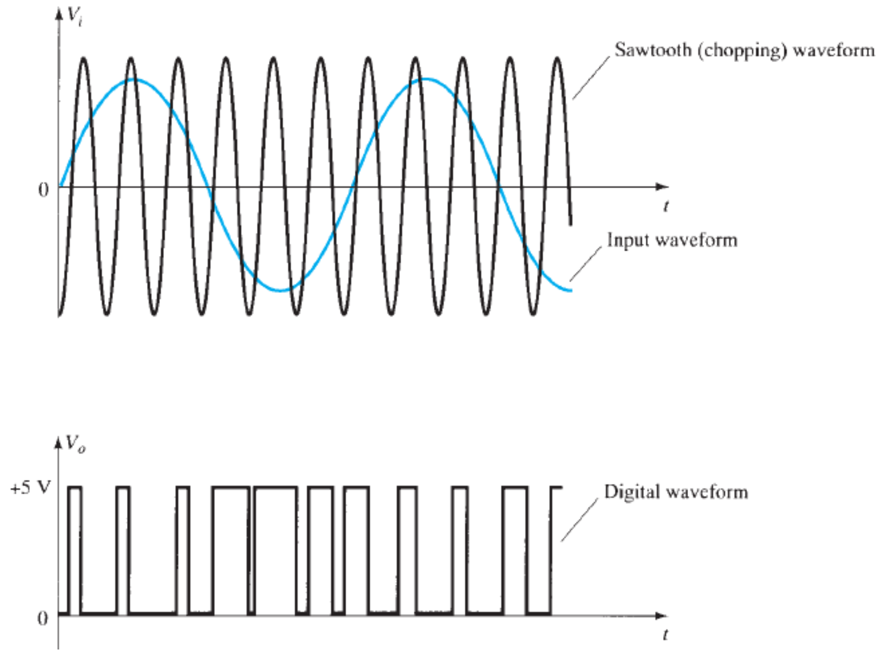


**FIG. 19:** *Chopping of a sinusoidal waveform to produce a digital waveform.*

Figure 20 shows a block diagram of the unit needed to amplify the class D signal and then convert back into the sinusoidal-type signal using a low-pass filter. Since the amplifier's transistor devices used to provide the output are basically either off or on, they provide current only when they are turned on, with little power loss due to their low "on" voltage. Since most of the power applied to the amplifier is transferred to the load, the efficiency of the circuit is typically very high. Power MOSFET devices have been quite popular as the driver devices for the class D amplifier.

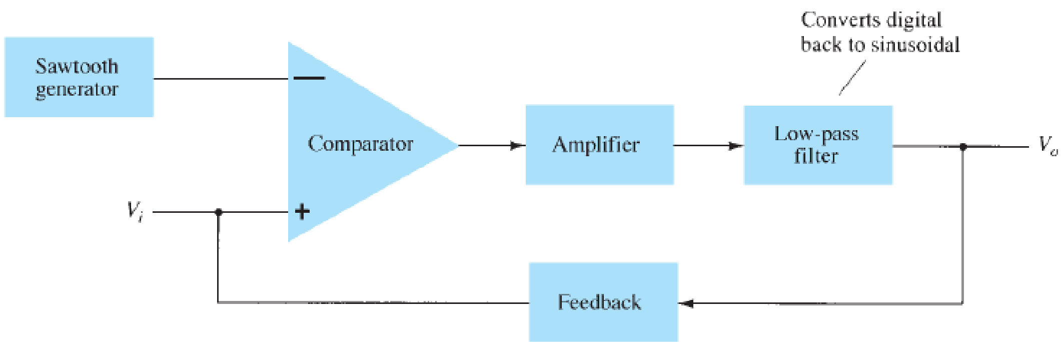


**FIG. 20:** *Block diagram of class D amplifier.*

# Feedback and Oscillator Circuits

## FEEDBACK CONCEPTS

Feedback has been mentioned previously in op-amp circuits. Depending on the relative polarity of the signal being feedback into a circuit, one may have negative or positive feedback. **Negative feedback** results in decreased voltage gain, for which a number of circuit features are improved, as summarized below. **Positive feedback** drives a circuit into oscillation as in various types of oscillator circuits.

A typical feedback connection is shown in Fig. 1 . The input signal $V_s$ is applied to a difference block, where it is combined with a feedback signal $V_f$ to produce $V_i$ which is then the input signal to the amplifier (A). A portion of the amplifier output $V_o$ is connected to the feedback block (□), which provides a feedback signal to the difference block.

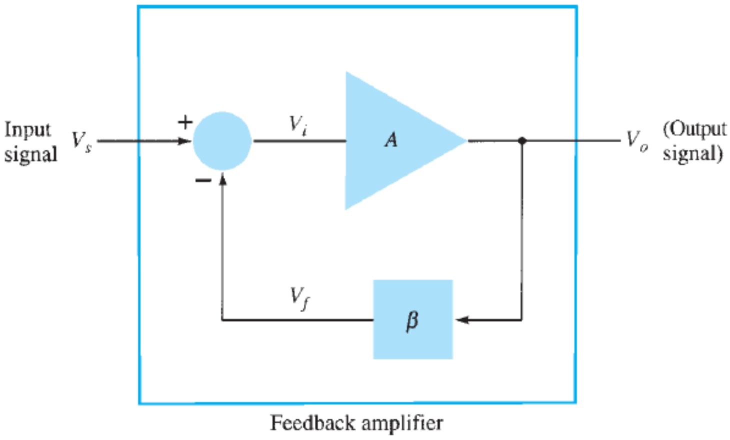


Fig.1

Although negative feedback results in reduced overall voltage gain, a number of advantages are obtained, among them being:

1. Higher input impedance.
2. Better stabilized voltage gain.
3. Improved frequency response.
4. Lower output impedance.
5. Reduced noise.
6. More linear operation.

## FEEDBACK CONNECTION TYPES

There are four basic ways of connecting the feedback signal. Both voltage and current can be feedback to the input either in series or parallel. Specifically, there can be:

1. Voltage-series feedback ( Fig. 2 a).
2. Voltage-shunt feedback ( Fig. 2 b).

3. Current-series feedback ( Fig. 2 c).

4. Current-shunt feedback ( Fig. 2 d).

In the list above, voltage refers to connecting the output voltage as input to the feedback network; current refers to tapping off some output current through the feedback loop. Series refers to connecting the feedback signal in series with the input signal voltage; shunt refers to connecting the feedback signal in shunt (parallel) with an input current source.

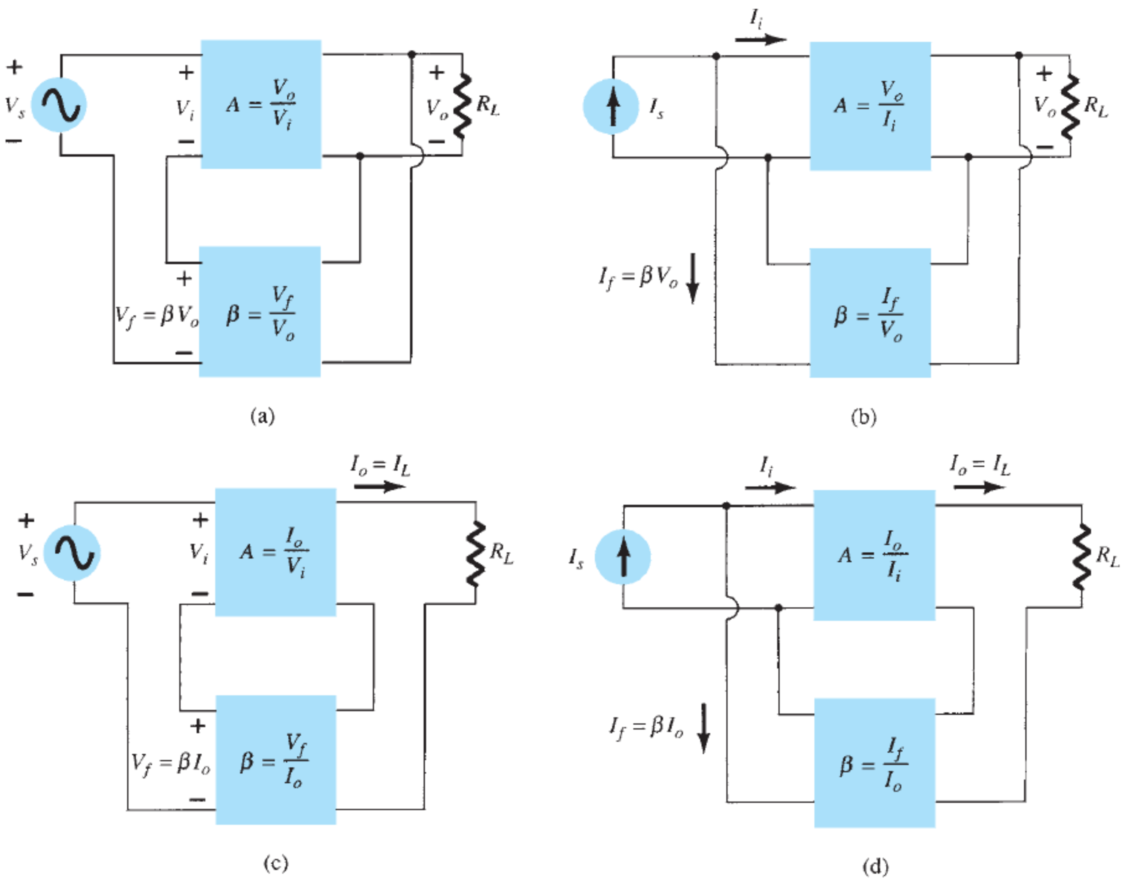


FIG. 2: Feedback amplifier types:

(a) voltage-series feedback, Af = Vo/Vs; (b) voltage-shunt feedback, Af = Vo/Is;

(c) current-series feedback, Af = Io/Vs; (d) current-shunt feedback, Af = Io/Is.

Series feedback connections tend to *increase* the input resistance, whereas shunt feedback connections tend to *decrease* the input resistance. Voltage feedback tends to *decrease* the output impedance, whereas current feedback tends to *increase* the output impedance. Typically, higher input and lower output impedances are desired for most cascade amplifiers. Both of these are provided using the voltage-series feedback connection.

**Gain with Feedback**

The gain without feedback, *A* , is that of the amplifier stage. With feedback □, the overall gain of the circuit is reduced by a factor (1 +□ *A* ). A summary of the gain, feedback factor, and gain with feedback of Fig. 2 is provided for reference in Table 1.

**TABLE 1** *Summary of Gain, Feedback, and Gain with Feedback from Fig. 2*

| | | Voltage-Series | Voltage-Shunt | Current-Series | Current-Shunt |
|---|---|---|---|---|---|
| Gain without feedback | $A$ | $\frac{V_o}{V_i}$ | $\frac{V_o}{I_i}$ | $\frac{I_o}{V_i}$ | $\frac{I_o}{I_i}$ |
| Feedback | $\beta$ | $\frac{V_f}{V_o}$ | $\frac{I_f}{V_o}$ | $\frac{V_f}{I_o}$ | $\frac{I_f}{I_o}$ |
| Gain with feedback | $A_f$ | $\frac{V_o}{V_s}$ | $\frac{V_o}{I_s}$ | $\frac{I_o}{V_s}$ | $\frac{I_o}{I_s}$ |

## 1- Voltage-Series Feedback

Figure 2-a shows the voltage-series feedback connection with a part of the output voltage fed back in series with the input signal, resulting in an overall gain reduction. If there is no feedback ($V_f = 0$), the voltage gain of the amplifier stage is:

$$A = \frac{V_o}{V_s} = \frac{V_o}{V_i} \qquad (1)$$

If a feedback signal $V_f$ is connected in series with the input, then

$$V_i = V_s - V_f$$

Since $V_o = AV_i = A(V_s - V_f) = AV_s - AV_f = AV_s - A(\beta V_o)$

then $(1 + \beta A)V_o = AV_s$

so that the overall voltage gain with feedback is

$$A_f = \frac{V_o}{V_s} = \frac{A}{1 + \beta A} \qquad (2)$$

Equation (2) shows that the gain with feedback is the amplifier gain reduced by the factor (1+□A). This factor will be seen also to affect input and output impedance among other circuit features.

**Input Impedance with Feedback**

A more detailed voltage-series feedback connection is shown in Fig. 3 . The input impedance can be determined as follows:

$$I_i = \frac{V_i}{Z_i} = \frac{V_s - V_f}{Z_i} = \frac{V_s - \beta V_o}{Z_i} = \frac{V_s - \beta AV_i}{Z_i}$$

$$I_i Z_i = V_s - \beta AV_i$$

$$V_s = I_i Z_i + \beta AV_i = I_i Z_i + \beta AI_i Z_i$$

$$Z_{if} = \frac{V_s}{I_i} = Z_i + (\beta A)Z_i = Z_i(1 + \beta A) \qquad (3)$$

The input impedance with series feedback is seen to be the value of the input impedance without feedback multiplied by the factor (1+□$A$ ), and applies to both voltage-series ( Fig. 2 a) and current-series ( Fig. 2 c) configurations.

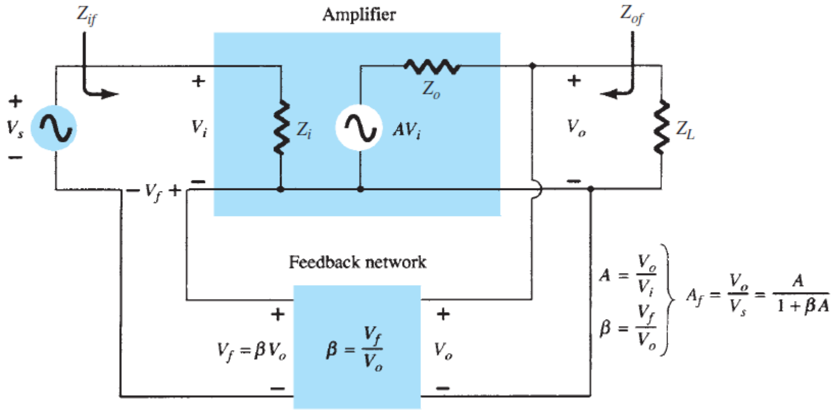


FIG. 3: Voltage-series feedback connection.

**Output Impedance with Feedback**

The output impedance for the connections of Fig. 2 is dependent on whether voltage or current feedback is used. For voltage feedback, the output impedance is decreased, whereas current feedback increases the output impedance.

For voltage-series feedback, the voltage-series feedback circuit of Fig. 3 provides sufficient circuit detail to determine the output impedance with feedback. The output impedance is determined by applying a voltage V , resulting in a current I , with **Vs** shorted out (Vs = 0). The voltage V is then

$$V = IZ_o + AV_i$$

For $V_s = 0$, $\quad V_i = -V_f$

so that $\quad V = IZ_o - AV_f = IZ_o - A(\beta V)$

Rewriting the equation as

$$V + \beta AV = IZ_o$$

allows solving for the output impedance with feedback:

$$Z_{of} = \frac{V}{I} = \frac{Z_o}{1 + \beta A} \qquad \textbf{(4)}$$

**2- Voltage-Shunt Feedback**

The gain with feedback for the network of Fig. 2-b is

$$A_f = \frac{V_o}{I_s} = \frac{A\,I_i}{I_i + I_f} = \frac{A\,I_i}{I_i + \beta V_o} = \frac{A\,I_i}{I_i + \beta A\,I_i}$$

$$A_f = \frac{A}{1 + \beta A} \qquad \textbf{(5)}$$

A more detailed voltage-shunt feedback connection is shown in Fig. 4. The input impedance can be determined to be

$$Z_{if} = \frac{V_i}{I_s} = \frac{V_i}{I_i + I_f} = \frac{V_i}{I_i + \beta V_o}$$

$$= \frac{V_i/I_i}{I_i/I_i + \beta V_o/I_i}$$

$$Z_{if} = \frac{Z_i}{1 + \beta A} \qquad \textbf{(6)}$$

This reduced input impedance applies to the voltage-series connection of Fig. 2-a and the voltage-shunt connection of Fig. 2-b.

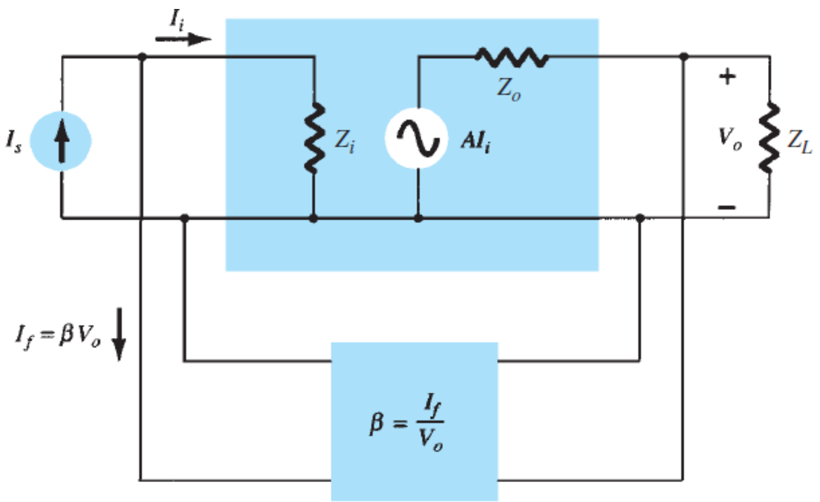


FIG. 4: Voltage-shunt feedback connection.

The output impedance with current-series feedback can be determined by applying a signal V to the output with Vs shorted out, resulting in a current I , the ratio of V to I being the output impedance. Figure 5 shows a more detailed connection with current-series feedback. For the output part of a current-series feedback connection shown in Fig. 5 , the resulting output impedance is determined as follows.

With V s =0,

$$V_i = V_f$$

$$I = \frac{V}{Z_o} - AV_i = \frac{V}{Z_o} - AV_f = \frac{V}{Z_o} - A\beta I$$

$$Z_o(1 + \beta A)I = V$$

$$Z_{of} = \frac{V}{I} = Z_o(1 + \beta A) \qquad \textbf{(7)}$$

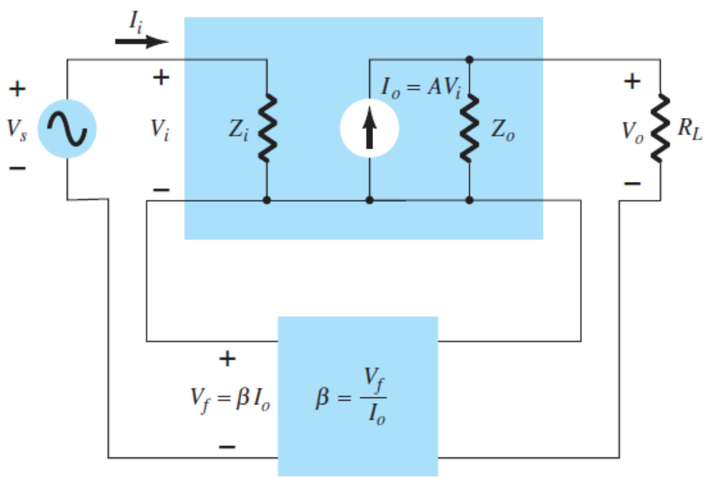


Fig.5

A summary of the effect of feedback on input and output impedance is provided in Table 2.

**TABLE 2** *Effect of Feedback Connection on Input and Output Impedance*

| | Voltage-Series | Current-Series | Voltage-Shunt | Current-Shunt |
|---|---|---|---|---|
| $Z_{if}$ | $Z_i(1 + \beta A)$ (increased) | $Z_i(1 + \beta A)$ (increased) | $\frac{Z_i}{1 + \beta A}$ (decreased) | $\frac{Z_i}{1 + \beta A}$ (decreased) |
| $Z_{of}$ | $\frac{Z_o}{1 + \beta A}$ (decreased) | $Z_o(1 + \beta A)$ (increased) | $\frac{Z_o}{1 + \beta A}$ (decreased) | $Z_o(1 + \beta A)$ (increased) |

**EXAMPLE 1** Determine the voltage gain, input, and output impedance with feedback for voltage-series feedback having $A = -100$, $R_i = 10\,\text{k}\Omega$, and $R_o = 20\,\text{k}\Omega$ for feedback of (a) $\beta = -0.1$ and (b) $\beta = -0.5$.

***Solution:***

a. $$A_f = \frac{A}{1 + \beta A} = \frac{-100}{1 + (-0.1)(-100)} = \frac{-100}{11} = \mathbf{-9.09}$$

$$Z_{if} = Z_i(1 + \beta A) = 10\,\text{k}\Omega\,(11) = \mathbf{110\,k\Omega}$$

$$Z_{of} = \frac{Z_o}{1 + \beta A} = \frac{20 \times 10^3}{11} = \mathbf{1.82\,k\Omega}$$

b. $$A_f = \frac{A}{1 + \beta A} = \frac{-100}{1 + (-0.5)(-100)} = \frac{-100}{51} = \mathbf{-1.96}$$

$$Z_{if} = Z_i(1 + \beta A) = 10\,\text{k}\Omega\,(51) = \mathbf{510\,k\Omega}$$

$$Z_{of} = \frac{Z_o}{1 + \beta A} = \frac{20 \times 10^3}{51} = \mathbf{392.16\,\Omega}$$

Example 1 demonstrates the trade-off of gain for desired input and output resistance. Reducing the gain by a factor of 11 (from 100 to 9.09) is complemented by a reduced output resistance and increased input resistance by the same factor of 11. Reducing the gain by a factor of 51 provides a gain of only 2 but with input resistance increased by the factor of 51 (to over 500 kΩ) and output resistance reduced from 20 kΩ to under 400 Ω. Feedback offers the designer the choice of trading away some of the available amplifier gain for other desired circuit features.

## PRACTICAL FEEDBACK CIRCUITS

Examples of practical feedback circuits will provide a means of demonstrating the effect feedback has on the various connection types. This section provides only a basic introduction to this topic.

### Voltage-Series Feedback

Figure 6 shows a voltage-series feedback connection using an op-amp. The gain of the op-amp, A , without feedback, is reduced by the feedback factor

$$\beta = \frac{R_2}{R_1 + R_2}$$

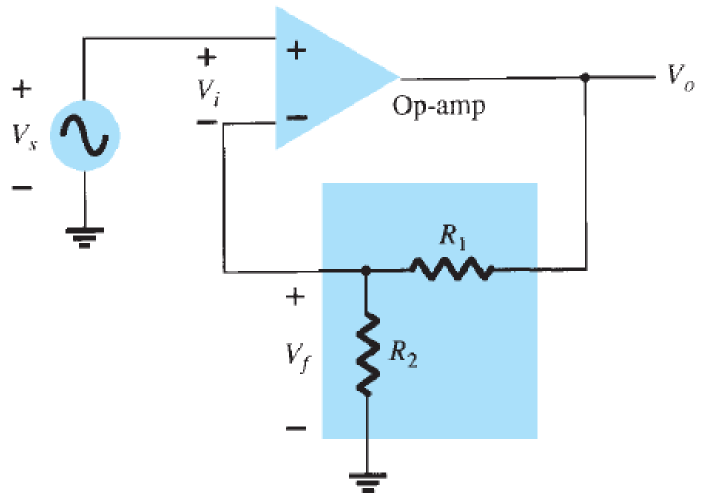


**FIG. 6:** *Voltage-series feedback in an op-amp connection.*

**EXAMPLE 2** Calculate the amplifier gain of the circuit of Fig. 5 for op-amp gain $A = 100{,}000$ and resistances $R_1 = 1.8\ \text{k}\Omega$ and $R_2 = 200\ \Omega$.

**Solution:**

$$\beta = \frac{R_2}{R_1 + R_2} = \frac{200\ \Omega}{200\ \Omega + 1.8\ \text{k}\Omega} = 0.1$$

$$A_f = \frac{A}{1 + \beta A} = \frac{100{,}000}{1 + (0.1)(100{,}000)}$$

$$= \frac{100{,}000}{10{,}001} = 9.999$$

Note that since $\beta A \gg 1$,

$$A_f \cong \frac{1}{\beta} = \frac{1}{0.1} = \mathbf{10}$$

**Voltage-Shunt Feedback**

The constant-gain op-amp circuit of Fig. 7-a provides voltage-shunt feedback. Referring to Fig.7- b and Table 1 and the op-amp ideal characteristics $Ii = 0$, $Vi = 0$, and voltage gain of infinity, we have

$$A = \frac{V_o}{I_i} = \infty$$

$$\beta = \frac{I_f}{V_o} = \frac{-1}{R_o}$$

The gain with feedback is then

$$A_f = \frac{V_o}{I_s} = \frac{V_o}{I_i} = \frac{A}{1 + \beta A} = \frac{1}{\beta} = -R_o$$

This is a transfer resistance gain. The more usual gain is the voltage gain with feedback,

$$A_{vf} = \frac{V_o}{I_s}\frac{I_s}{V_1} = (-R_o)\frac{1}{R_1} = \frac{-R_o}{R_1}$$

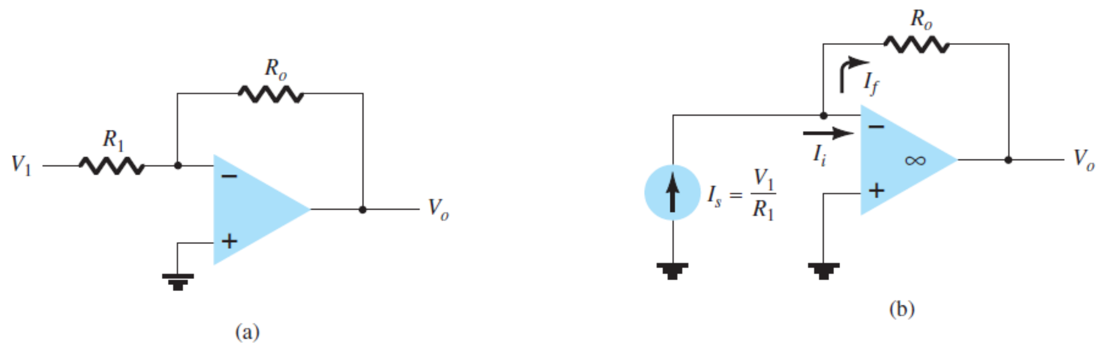


**FIG. 6:** *Voltage-shunt negative feedback amplifier: (a) constant-gain circuit; (b) equivalent circuit.*

**SUMMARY of Equations**

Voltage-series feedback:

$$A_f = \frac{V_o}{V_s} = \frac{A}{1 + \beta A}, \qquad Z_{if} = \frac{V_s}{I_i} = Z_i + (\beta A)Z_i = Z_i(1 + \beta A),$$

$$Z_{of} = \frac{V}{I} = \frac{Z_o}{(1 + \beta A)}$$

Voltage-shunt feedback:

$$A_f = \frac{A}{1 + \beta A}, \qquad Z_{if} = \frac{Z_i}{(1 + \beta A)}$$

Current-series feedback:

$$Z_{if} = \frac{V}{I} = Z_i(1 + \beta A), \qquad Z_{of} = \frac{V}{I} = Z_o(1 + \beta A)$$

Current shunt feedback:

$$Z_{if} = \frac{Z_i}{(1 + \beta A)}, \qquad Z_{of} = \frac{V}{I} = Z_o(1 + \beta A)$$