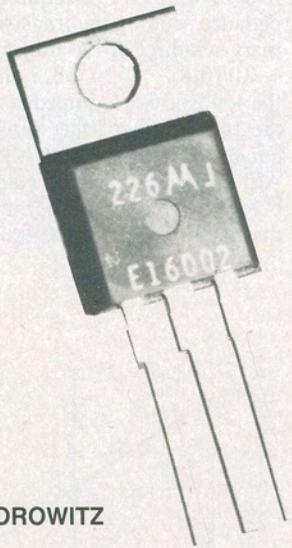


How to Design Analog Circuits —Power Amplifiers



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The various types of power amplifiers, and some important factors to consider when designing those circuits, are the topics we'll cover in this month's article.

A TRANSISTOR DELIVERS POWER TO THE load or device connected to it. If we're looking at a DC amplifier, the power delivered is, of course, equal to the load resistance multiplied by the square of the DC current flowing through that load.

In the case of an AC amplifier, however, things get a little more complicated. Should a full cycle appear across the load, the relationship of power to current and resistance remains the same as in the DC case, but now the effective current is the peak current in the cycle divided by the square root of 2. If, on the other hand, only one-half of the cycle appears (with zero output during the other), the effective current now becomes the peak current divided by 2. When more than one-half of a cycle of current flows but there is less than a full cycle, the effective current in the resistor is somewhere between the two.

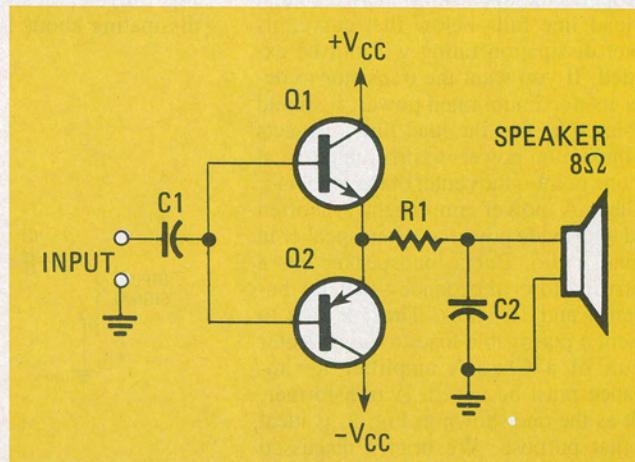
The portion of the cycle that appears across the output load is determined by the class of operation of the amplifier being used. Large signal transistor power-amplifiers operate in Class-A through -H. Most audio and RF circuits, however, are designed for Class-A, -AB, -B and -C operation. Special con-

siderations are involved when a design calls for a circuit to operate in the Class-D through -H modes. In this discussion, therefore, we will briefly look at the latter classes, but concentrate on designs involving the four more-popular ones.

In Class-A circuits, current flows through the transistor over the complete cycle and bias is set at the center of the transistor's load line. In Class-B circuits, the current flows only during one half of a cycle and the transistor's bias current is set for $I_C = 0$. In Class-AB operation, current flows through the transistor during one half of the cycle and part of the other one. Finally, in Class-C operation, current flows through the transistor for less than one half cycle.

Class-A amplifiers

Class-A amplifiers that are designed to reproduce low-power signals are usually biased at the center of their load line. Class-A power amplifiers are also ideally biased at that point but some additional factors must be considered. For one thing, to deliver power, a transistor must dissipate power. Despite the size of the load, the product of the collector current and collector-to-emitter voltage at any



point on the load line, must be less than the power dissipation rating of the transistor if the device is not to be destroyed. That condition will be met if the load line for the device is chosen so that it falls below the maximum permissible power-dissipation curve of the device.

Let's now look at how that power-dissipation curve is derived and how it is used in determining the load line. As an example, assume that the circuit we are designing uses a transistor that can dissipate 10 watts and handle a maximum collector current of 1 amp. If you were now to calculate the maximum allowable voltage for currents of from zero- to one-amp, you would wind up with the data shown in Table 1. Plotting that data as shown in Fig. 1 gives you the maximum

TABLE 1

Current (amps)	Voltage (volts)
0	∞
0.1	100
0.2	50
0.4	25
0.5	20
0.8	12.5
1	10

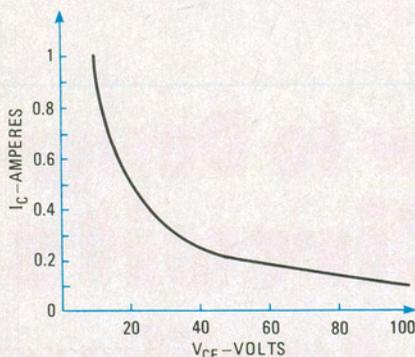


FIG. 1—THE MAXIMUM POWER dissipation curve for a transistor is plotted here using the data from Table 1.

power-dissipation curve for the device. As long as the transistor is biased so that its load line falls below that curve, its power-dissipation rating will not be exceeded. If you want the transistor to deliver its maximum rated power, it should be biased so that the load line intersects the maximum power-dissipation curve at just one point—the center of the load line.

Class-A power amplifiers are often used to provide power to a loudspeaker in a small radio. But a loudspeaker has a relatively low impedance—usually between 4 and 16 ohms. Thus, if it is to present a reasonable load to the collector circuit of a Class-A amplifier its impedance must be raised. A transformer, such as the one shown in Fig. 2, is ideal for that purpose. We briefly discussed transformer principals in the article that appeared in the December 1982 issue of **Radio-Electronics**. As stated there, the impedance of the primary is related to the impedance of the secondary by $Z_p/Z_s = (N_p/N_s)^2$. Thus, if an amplifier circuit has an output impedance of 72 ohms but you wish to use the circuit to drive an 8-ohm speaker, you'll need an impedance-matching transformer with a turns ratio equal to $\sqrt{Z_p/Z_s} = \sqrt{78/8}$, or 3:1.

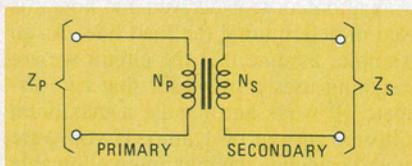


FIG. 2—A TRANSFORMER is used to alter the impedance of the load seen by the transistor.

When a transformer is used between the loudspeaker and transistor in a Class-A amplifier, the maximum efficiency of the overall circuit is 50%. That is, the maximum sinusoidal power that can be delivered to the load is equal to 50% of the power that must be supplied by the power source and dissipated by the transistor when idling. Thus, while a transistor can be biased to demand a maximum of 10 watts from a supply, only 5 watts would be delivered to the load over a cycle; the

remaining power is dissipated by the transistor.

While that 50% sounds low, in reality the efficiency is even 20% to 40% lower because of the losses and limits of the circuit and transformer. As bad as that is, it could be worse. If you attempted to place the load directly in the collector circuit instead of using a transformer, DC power would be dissipated by the load as well, limiting the maximum efficiency to about 25%. That will still be reduced by the same 20% to 40% we mentioned earlier, leaving us with an efficiency of about 20%, if we are lucky.

Let's now assume that you want to design a Class-A amplifier to deliver 4 watts to an 8-ohm loudspeaker. If a transformer is used in the circuit as shown in Fig. 3-a, the transistor must be capable of dissipating about 10 watts. If you use a

livering safely.

The AC load line is determined by the impedance reflected into the primary of the transformer, but it must pass through the quiescent point established by the DC-bias conditions. Because it must vary around that point, the collector voltage may swing from 0 to double the supply voltage, or to 50 volts. Similarly, the collector current can vary through a cycle from 0 to double the quiescent current, or to 0.8 amps. Consequently, the impedance seen by the transistor in the primary winding of the transformer, is $(50 - 0)/(0.8 - 0) = 62.5$ ohms. Because the loudspeaker's impedance is 8 ohms, the turns ratio of the transformer must equal $\sqrt{62.5/8} = 2.8:1$. All points on the AC load line must, of course, be at or below the maximum permissible power dissipation curve of the transistor.

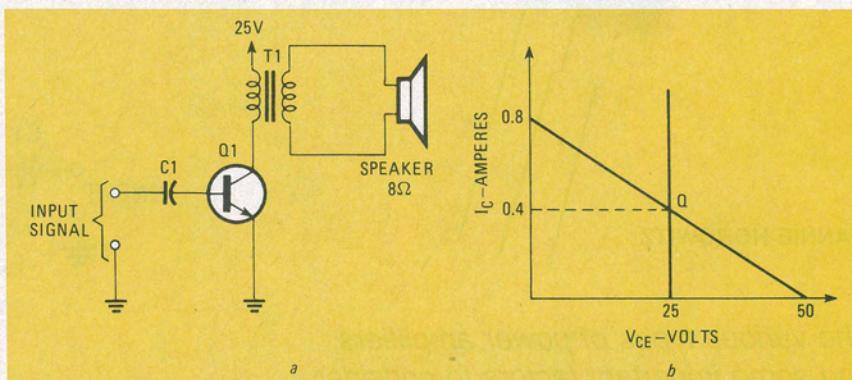


FIG. 3—A CLASS-A AMPLIFIER is shown in a; the load lines for the circuit are shown in b.

25-volt power supply, your load lines will look like those shown in Fig. 3-b.

(As mentioned in the December issue of **Radio-Electronics**, when a transformer couples a load to the transistor circuit, the collector sees DC load that consists of the winding resistance of the transformer primary along with any other resistance in the collector circuit. It also sees an AC load due to the reflection through the transformer of the load in the secondary. The quiescent operating point for the circuit is where those two load lines cross.)

Start the design by drawing the DC load line. The slope of that line equals the total DC resistance in the collector circuit. In our example, that is assumed to be close to 0 as the only element in the collector circuit is the primary of the transformer. The DC load-line is therefore a vertical line at V_{ce} equals 25 volts. Because the maximum power the transistor can dissipate is 10 watts, the maximum current that may flow through the transistor with 25 volts applied is $10/25 = 0.4$ amps. Therefore, the Q or quiescent point is 25 volts, 0.4 amps. Any bias current below that level may have been chosen on the DC load line, but the delivered power would not have been less than the maximum that the transistor is capable of de-

Class-B amplifiers

Since in Class-B operation a transistor is biased at the point where the quiescent or idling current is equal to zero, in that mode of operation current flows during just one-half of a cycle. Thus, assuming an NPN transistor for example, the only time current flows through the device is when the positive portion of the cycle is applied to its base. No current flows during the other half of the cycle. A simple Class-B amplifier is shown in Fig. 4.

If you want a Class-B amplifier to reproduce the entire input cycle, two transistors must be used in the circuit. One of those reproduces one half of the cycle while the other reproduces the second half of the cycle. The two halves are recom-

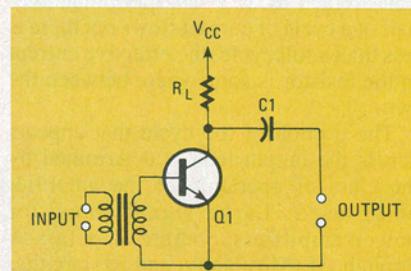


FIG. 4—IN A CLASS-B AMPLIFIER, current flows only during one half of a cycle.

combined across the load to produce an amplified version of the input waveform. Such a circuit, called a push-pull amplifier, is shown in Fig. 5. It gets its name from the fact that when one transistor conducts, the other is off. In Fig. 5, the relative phases of the applied signals are shown at the bases of the transistors; the outputs are shown along the leads from the collectors. Note that the lower device is turned on during the first half of each cycle while the upper transistor is turned on during the second half.

Considering the transformer circuit in Fig. 5 along with the loudspeaker load resistance, the impedance reflected from the secondary into the primary of the transformer is $R_L' = (N_p/N_s)^2 R_L$, where R_L and R_L' are the resistance of the loudspeaker and the impedance reflected back from the secondary into the full primary winding, respectively, and N_p/N_s is the ratio of the number of turns in the primary winding to the number of turns in the secondary winding. From that, it can be determined that the impedance each transistor sees, R_L'' , is equal to $R_L'/4$.

The power required to operate the circuit shown in Fig. 5 over an entire cycle is equal to $I_{C_{MAX}} V_{CC}/1.57$. The maximum power that the circuit can deliver to the load is 78.5% of the full-cycle power demanded from the supply. Power delivered to the load over the complete cycle, is double the maximum instantaneous power each transistor dissipates during the cycle, or $V_{CC} I_{C_{MAX}}/2$.

We noted in our discussion of Class-A amplifiers that the load line of a transistor must not cross or go above the maximum-power-dissipation curve. That does not hold for Class-B operation because the transistors conduct for just one-half of each cycle and the total power dissipation is found by averaging over a complete cycle. Considering that, the load line may cross the power-dissipation curve, or a portion of it may even lie above that curve, provided that the average power dissipated by the transistor during the complete cycle does not exceed the transistor's stated maximum power-dissipation rating.

The amount of power actually dissipated by a transistor, depends upon the portion of the maximum output power that is actually delivered to the load. When the power across the load is 40% of the maximum output signal that can be supplied by the circuit, maximum power is dissipated by the transistor. If the output is more or less than 40% of the maximum, the transistor will demand less than the maximum power from the supply.

To check the temperature rise of the output transistors, set the amplifier up so that it delivers 40% of the maximum power to the load. Allow the circuit to operate that way for several hours, then check to see if the temperature of the transistor has exceeded its upper limit and whether or

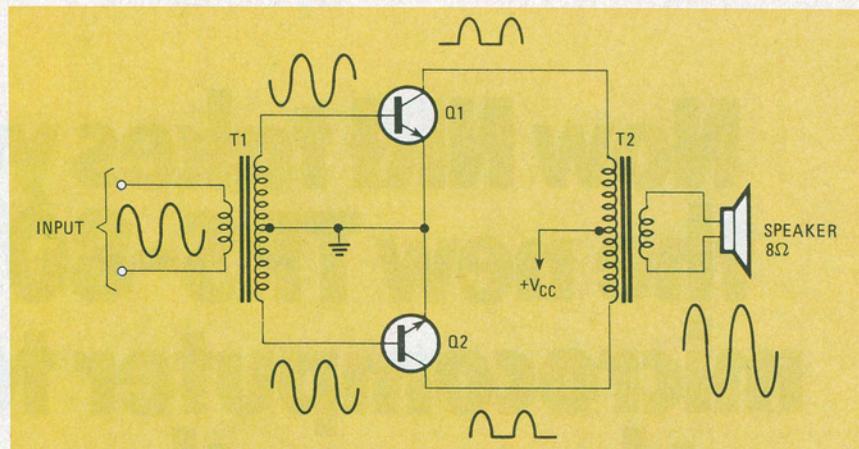


FIG. 5—IF YOU WANT a Class-B amplifier to reproduce an entire cycle, two transistors must be used in a push-pull configuration as shown here. Note that the relative phases of the signal at various points in the circuit are also shown.

not the device is still working.

Although two transistors are used in a push-pull circuit, the design revolves around one device at a time. The first step is to decide how much power, $P_{RL''}$, must be delivered by the overall circuit. Each device, then, must deliver one half of that power; the overall circuit is arrived at by designing the appropriate circuit for each transistor.

The first step is to select transistors that are capable of handling the amount of power that they will be called on to dissipate. If the supply voltage is V_{CC} , the load, R_L'' , seen by one transistor is $V_{CC}^2/4P_{RL''}$. The maximum average power dissipated by the transistor is found from $P_{MAX} = V_{CC}^2/\pi^2 R_L''$. That is, of course, the power dissipated when 40% of the maximum output is developed at the output. Select a transistor that is capable of dissipating that power.

Turning to the transformers, they are chosen as discussed in the December 1982 issue of **Radio-Electronics** (see that issue for a full discussion of the technique). Bear in mind that the impedance that must be seen across the entire primary winding of transformer T2 is $4R_L''$. Thus, if the impedance presented by the load to the secondary winding is R_L , the transformer turns ratio should be equal to $\sqrt{4R_L''/R_L}$. Also, the primary must be center-tapped.

Class AB amplifiers

In Class-A operation, the output transistor is biased at the center of the load line, while in Class-B, it is biased at the point where no collector current flows when the transistor is in the quiescent or idling state. In Class-AB operation, the transistor is biased to operate at a point somewhere between Class-A and Class-B. In that mode, some collector current flows when the device is idling. Although that decreases the efficiency of the circuit, Class-AB operation is useful where good and reliable reproduction of the input signal is required.

As noted in our earlier discussions of

diodes and transistors, no (or very little) conduction takes place through those devices unless somewhat more than a specific minimum voltage is applied to their terminals. Essentially no current flows through the base-emitter junction of a germanium transistor if less than about 0.2 or 0.3 volt is applied. Similarly, a minimum of between 0.5 and 0.7 volt must be applied to the junction of a silicon device before any current will flow.

If we rely only on a signal at the input of the circuit to turn on a transistor, it will not be turned on until that input exceeds the required minimum voltage. A sine-wave at the input will therefore be distorted after being amplified by a Class-B circuit as is shown in Fig. 6. Here, there is no signal at the crossover point during the time when one transistor of the push-pull pair stops conducting and the second one

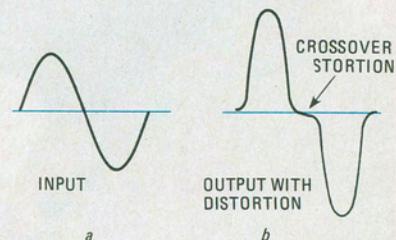


FIG. 6—CROSSOVER DISTORTION, shown in b, occurs because a transistor does not conduct at low input-signal levels.

begins.

Although that distortion is undesirable, it may be acceptable for some applications. But what may be even more critical in Class-B operation is that when a transistor is cut off at a rapid rate, large transient voltages develop in the circuit. As a result, the transistor may break down.

To avoid breakdown while minimizing distortion, the transistor is biased so that some collector current flows when the circuit is idling. That current is usually

between 10 and 25 mA, although idling current as high as 300 mA can be used in high-power designs. Distortion can be reduced farther by using a diode in series with each emitter load in the transistors of the push-pull circuit. That diode rounds off the crossover point to a greater degree than is possible when only the junction of the transistor is in the circuit.

Class-C amplifiers

In the Class-C mode of operation, the transistor is biased so that it conducts for less than one-half of a cycle. To do that using an NPN device, the base is biased negative with respect to the emitter. As the output is obviously in the form of pulses, the efficiency in some cases can be as high as 85%.

Although not useful in audio applications, the Class-C amplifier is frequently used in RF circuits. A resonant L-C circuit is placed at its output. Each time a signal is applied to the amplifier's input, a full cycle is generated across the L-C circuit, provided that circuit is tuned for the frequency (or a multiple of the frequency) of the signal applied to the amplifier's input.

Class-D through Class-H amplifiers

We could devote quite a bit of space to detailing the various other classes of operation, and how to design circuits using those modes of operation. Because the usefulness of those modes is limited mainly to special circuits and applications, we will just briefly note what they are. Each class is characterized by high efficiency and some boast excellent fidelity.

Class-D amplifiers are used to convert audio signals to pulses. In some designs, up to one-half million of those pulses are produced each second. When audio is converted to pulses, the width of each pulse is related to the instantaneous amplitude of the audio signal. When reproduced through an amplifier, the pulses are fed to a push-pull circuit. The output from the circuit is connected through a resistor to a loudspeaker that is shunted by a capacitor, as shown in Fig. 7. You'll note that no transformer is used between the load and transistors; instead, the transistors feed the amplified pulse signals directly

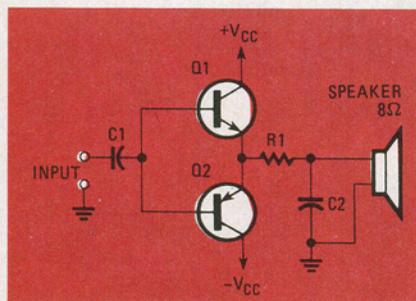


FIG. 7—IN A CLASS-D AMPLIFIER an audio input is converted to pulses and then reconverted to amplified audio.

to the loudspeaker through resistor R1. Resistor R1 and capacitor C2 form an integrator circuit where the width of each pulse determines the voltage developed across C2 and hence across the loudspeaker. That converts the pulses back to audio, which is output through the speaker.

Class-E, -F, and -G amplifiers are quite similar. In each half of the push-pull circuit, two transistors are connected in series. When the input signal is low, only one of the transistors in each half of the push-pull circuit conducts current, while no voltage is applied to the remaining devices. When the input signal is high, the transistors in both halves of the push-pull circuits are turned on. Since all the transistors conduct only during the peaks in the audio input signal, efficiency is quite high.

Class-H amplifiers use logic circuits in an otherwise standard push-pull amplifier. Normal or average levels of audio are reproduced in the usual Class-AB fashion. When input signals are large, however, the logic circuit activates the power supply to provide high voltages to the push-pull transistors. Because the supply voltage and hence the power dissipation are both low during the greater part of the audio cycle, the efficiency of the circuit is high.

The various classes of operation described here, are not the only means of improving distortion and efficiency. Bi-amplification can be added to the list. In that arrangement, the entire audio signal is fed to a filter such as the one shown in Fig. 8. At its outputs, the audio bandwidth is split into two bands—a band of high frequencies and a band of low frequencies—and each is amplified by a different push-pull amplifier. Each amplifier is designed to reproduce a particular band most efficiently. The crossover frequency, f_1 , is usually chosen to be anywhere between 400 and 800 Hz. At f_1 , gain has decreased somewhat on the low frequency band and increased an equal amount on the high frequency band. The values of the inductors and capacitors in the circuit can be found using the formula given in the figure; R is the resistance presented to the filter by the input circuit of the amplifier.

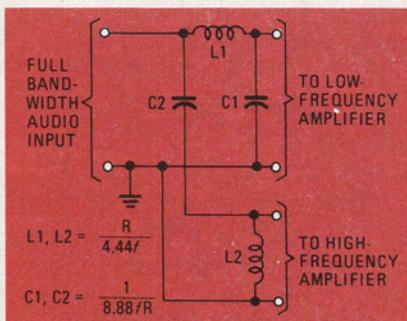


FIG. 8—USING A FILTER and bi-amplification, as shown here, can improve efficiency and reduce distortion.

VFET's and MOSFETS

Although bipolar power-amplifiers were considered in detail, the power FETs—the VFET and MOSFET—are now becoming popular. Those devices are used in push-pull circuits similar to those using bipolar devices. Just as the base-emitter current of the bipolar device was adjusted for a predetermined idling collector current, the gate-source voltage of the FET power amplifiers must be adjusted for a desirable idling drain-current level. Power FET circuits may be considered to operate in the Class-AB mode, but it is not unusual for the drain current to be set to a level as high as 500 mA. Distortion is low because the amplification characteristics of those devices are essentially linear.

Solutions to thermal problems

When a transistor dissipates power, it gets hot. That heat must be removed from the transistor if it is not to overheat and be destroyed. If heat is not removed from a bipolar device, its collector current builds up. If that build-up is not controlled and limited, the current level and power dissipated by the device may become excessive and exceed safe levels of operation, resulting in breakdown. Although that type of current build-up does not occur in the drain circuit of the VFET as its temperature rises, the VFET can break down if excess heat is not removed from the device at a reasonable pace. Here, we will describe methods of removing heat from the bipolar device. The discussion, of course, also applies to FET's.

There is a thermal resistance that impedes the dissipation of heat from the junction of the transistor to the surrounding air. That resistance, called θ_{JA} , is in units of $^{\circ}\text{C}/\text{watt}$. The temperature of the junction, T_J , depends upon the temperature of the air, T_A , around the transistor and the average power, P_{diss} , being dissipated by the device over a relatively short period of time. Those factors are related to each other by the equation:

$$P_{\text{diss}} = \frac{T_J - T_A}{\theta_{JA}} \quad (1)$$

The thermal resistance θ_{JA} consists of three thermal resistances. Those are θ_{JC} , the thermal resistance from the junction to the case, θ_{CS} , the thermal resistance from the case to a heat sink, and θ_{SA} , the thermal resistance from the heat sink to the surrounding air. Using those resistances, equation 1 becomes:

$$P_{\text{diss}} = \frac{T_J - T_A}{\theta_{JC} \theta_{CS} + \theta_{SA}}$$

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ANALOG CIRCUITS

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To keep a transistor from overheating, it's usually mounted on a metal surface known as a heat sink. Air flows over that surface, cooling it. In turn, it cools the case of the transistor. The heat sink reduces the thermal resistance from the case to the air, θ_{CA} . As $\theta_{CA} = \theta_{CS} + \theta_{SA}$, equation 1 can also be written as:

$$P_{diss} = \frac{T_J - T_A}{\theta_{JC} + \theta_{CA}}$$

The upper limit of P_{diss} that a transistor can tolerate is provided by the manufacturer of the device and can be found on the device's data sheet. That specification is usually given at a particular case temperature. The amount of power that the device can dissipate safely does not increase if the case temperature drops below that given in the specifications, but does drop if the temperature exceeds it. Curves may also be supplied to indicate the maximum power that the transistor can dissipate at different temperatures. When the curve is not made available, the manufacturer will supply a derating factor, given in watts/°C. That derating factor indicates how much the power dissipation rating must be reduced for every degree the temperature is above that specified in the maximum dissipation rating. Most often, the power dissipation is given at a case temperature of 25°C.

Let's look at an example of how to select and design a heat sink. Assume that the transistor you are using is specified as being capable of dissipating 115 watts when the case temperature is 25°C. If the derating factor is 0.8 watts/°C at a case temperature of 90°C, then the power-dissipation capability of the device drops to $115 - 60 = 55$ watts. Your circuit should be designed so that no more than 55 watts is dissipated by the transistor.

Using that information, assume that a silicon device with a maximum permissible junction temperature of 175°C is used. If the temperature of the air is 30°C, θ_{JA} is equal to:

$$\theta_{JA} = \frac{175^\circ\text{C} - 30^\circ\text{C}}{55 \text{ watts}} = 2.6^\circ\text{C/watt}$$

If θ_{JC} is 1.25°C/watt, $\theta_{CA} = \theta_{JA} - \theta_{JC} = 2.6 - 1.25 = 1.35^\circ\text{C/watt}$.

As θ_{CA} consists of $\theta_{CS} + \theta_{SA}$, it is desirable to make both factors as small as possible. θ_{CS} can be made very small by putting heat-conducting compound such as silicon grease between the case and sink. If the case is directly on the sink through that grease, θ_{CS} can become as low as 0.1°C/watt. Frequently, the case

must be insulated from the sink with a mica washer. Now, θ_{CA} can rise to 0.4°C/watt.

Assume that a mica washer must be used. In our example, θ_{SA} becomes $1.35 - 0.4 = 0.95^\circ\text{C/watt}$. It is possible to buy sinks with a similar or lower θ_{SA} resistance. A makeshift sink can be constructed from 1/8-inch-thick flat aluminum. If the total area on both surfaces of the metal is kept vertical and exposed to air, the areas of one side of the sink should be at least $750/\theta_{SA}^2$ square inches.

Some sinks are not merely a flat surface but have fins. Those sinks should be mounted in a location with good air flow and so that the fins are vertical.

Other important factors

In addition to case temperature, there are many other factors that affect the survival of a transistor. For one thing, over its lifetime, the case temperature of a transistor will rise and fall many times. There is a limit, however, to the number of times that can occur before the device will break down. That thermal cycling data is supplied by some manufacturers in the form of curves relating the power dissipated by the transistor, the amount the case-temperature rises, and the number of times this temperature can rise and fall, before the transistor may break down. A proper heat sink can help prevent that breakdown.

Another type of breakdown phenomenon in bipolar devices is when the base loses control of the collector current. Despite any drops in V_{CE} , the collector current keeps rising until the transistor is destroyed. To minimize that problem, select a transistor that will perform up to the highest frequency you need in your design but not above it and do not use a higher collector-emitter voltage than you absolutely require.

One final point: do not ignore the voltage, current, and power limits set for the bipolar or FET device you are using. Do not ignore transients—especially if an inductor is used in the circuit. Also, remember that the transistor will tolerate a higher collector-emitter voltage when the resistor shunting the base-emitter circuit of the transistor is at its lowest value. So keep that resistance small and keep some collector current flowing at all times.

Practical circuits

The information presented here can be used to design many different types of power amplifiers. Transformer coupling was used in the circuits described in this article because the essential operating characteristics of the different amplifier classes can be most easily described using those circuits. Most audio and other power amplifiers, however, do not use transformer coupling. Next time, we'll discuss modern power amplifier circuits, and how to keep them from breaking down in use.