EXERCISE

1.4 Three amplifiers with the following characteristics are cascaded.

1. Amplifier 1 : $A_{vo1} = 10$, $R_{i1} = 1\,\text{k}\Omega$, $R_{o1} = 100\,\Omega$
2. Amplifier 2 : $A_{vo2} = 20$, $R_{i2} = 2\,\text{k}\Omega$, $R_{o2} = 200\,\Omega$
3. Amplifier 3 : $A_{vo3} = 30$, $R_{i3} = 3\,\text{k}\Omega$, $R_{o3} = 300\,\Omega$

Find the parameters for the simplified model of the cascaded amplifier. Assume that the amplifiers are cascaded in the order 1, 2, 3.

Answer $R_i = 1\,\text{k}\Omega$, $R_o = 300\,\Omega$, $A_{vo} = 5357$.

EXERCISE

1.5 Repeat Exercise 1.4 if the order of the amplifiers is changed to 3, 2, 1.

Answer $R_i = 3\,\text{k}\Omega$, $R_o = 100\,\Omega$, $A_{vo} = 4348$.

1.6 POWER SUPPLIES AND EFFICIENCY

Power is supplied to the internal circuitry of amplifiers from a **power supply**. The power supply typically delivers current from several dc voltages to the amplifier—one configuration is illustrated in Figure 1.22. The average power supplied to the amplifier by each voltage source is the product of the average current and the voltage. The total power supplied is the sum of the powers supplied by each voltage source. For example, the total average power supplied to the amplifier of Figure 1.22 is

$$P_s = V_{AA} I_A + V_{BB} I_B \tag{1.8}$$

It is customary to use uppercase symbols with repeated uppercase subscripts, such as V_{CC}, for dc supply voltages in electronic circuits.

Note that we have assumed that the current directions in the supply voltages are such that both sources deliver power to the amplifier. Rarely, a condition occurs for which some of the power taken from one supply voltage is returned to another source. Sometimes we may only have a single supply voltage, or there can be several, so the number of terms in a supply-power calculation such as Equation (1.8) is variable. It is customary to use uppercase symbols with repeated uppercase subscripts, such as V_{CC}, for dc supply voltages in electronic circuits.

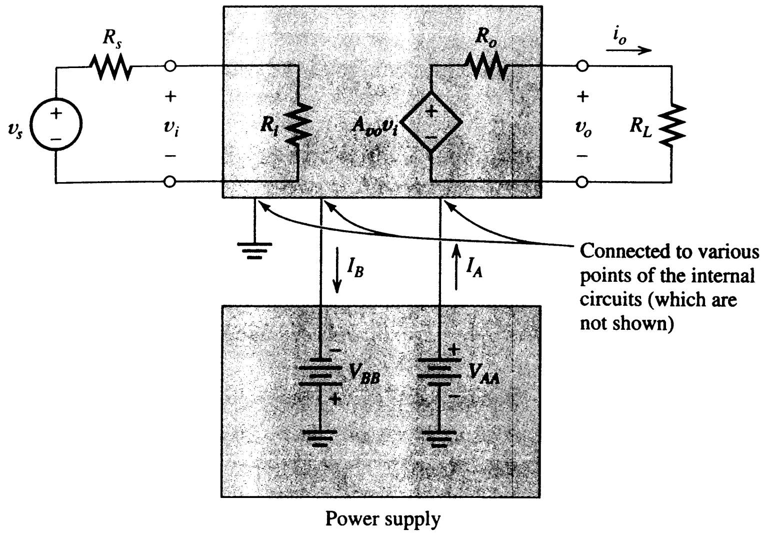


Figure 1.22 The power supply delivers power to the amplifier from several constant voltage sources.

We have seen that the power gain of typical amplifiers can be very large. Thus, the output power delivered to the load is much greater than the power taken from the signal source. This additional power is obtained from the power supply. Furthermore some of the power taken from the power supply is **dissipated** as heat in the internal circuits of the amplifier. Such dissipation is an undesirable effect that we usually try to minimize when designing the internal circuitry of an amplifier.

Power dissipation is the power that is converted to heat within the amplifier.

The sum of the power P_i entering the amplifier from the signal source and the power P_s from the power supply must be equal to the sum of the output power P_o and the power dissipated P_d. That is,

$$P_i + P_s = P_o + P_d \qquad (1.9)$$

Key equation relating powers in an amplifier.

which is illustrated in Figure 1.23. Often, the input power P_i from the signal source is insignificant compared with the other terms in this equation.

To summarize, we can view an amplifier as a system that takes power from the dc power supply and converts part of this power into output signal power. For example, a stereo audio system converts part of the power taken from the power supply into signal power that is finally converted to sound by the loudspeakers.

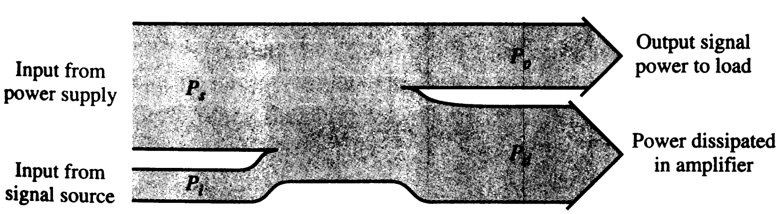


Figure 1.23 Illustration of power flow.

Power Efficiency

The **efficiency** η of an amplifier is the percentage of the power supplied that is converted into output power:

Key equation defining amplifier efficiency.

$$\eta = \frac{P_o}{P_s} \times 100\% \qquad (1.10)$$

Example 1.4 Determining the Power Efficiency of an Amplifier

Find the input power, output power, supply power, and power dissipated in the amplifier shown in Figure 1.24. Also, find the efficiency of the amplifier.

SOLUTION The average signal power delivered to the amplifier is given by

$$P_i = \frac{V_i^2}{R_i} = 10^{-11} W = 10\,\text{pW}$$

(Recall that 1 pW = 1 picowatt = 10^{-12} W.) The output voltage is

$$V_o = A_{vo} V_i \frac{R_L}{R_L + R_o} = 8\,\text{V rms}$$

We find the average output power as

$$P_o = \frac{V_o^2}{R_L} = 8\,\text{W}$$

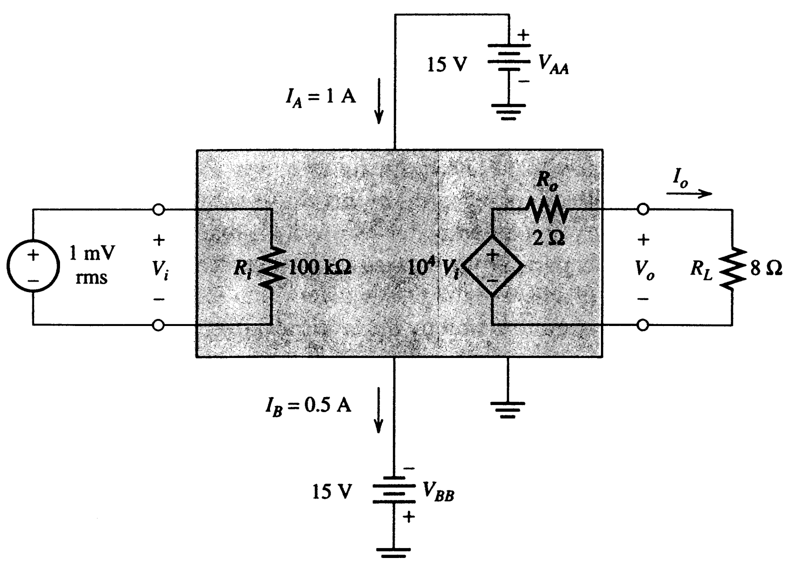


Figure 1.24 Amplifier of Example 1.4.

The supply power is given by

$$P_s = V_{AA}I_A + V_{BB}I_B = 15 + 7.5 = 22.5\,\text{W}$$

Notice that (as often happens) the input signal power is insignificant compared with the output and supply powers. The power dissipated as heat in the amplifier is

$$P_d = P_s + P_i - P_o = 14.5\,\text{W}$$

and the efficiency of the amplifier is

$$\eta = \frac{P_o}{P_s} = 35.6\%$$

The values given in this example are typical of one channel of a stereo amplifier under high-output test conditions. ❑

EXERCISE

1.6 A certain amplifier is supplied with 1.5 A from a 15-V supply. The output signal power is 2.5 W and the input signal power is 0.5 W. Find the power dissipated in the amplifier and the efficiency.

Answer $P_d = 20.5\,\text{W}$, $\eta = 11.1\%$.

1.7 DECIBEL NOTATION

Power gain is often expressed in **decibels** (dB) as

$$G_{\text{dB}} = 10 \log G \qquad (1.11)$$

Key equation for conversion of power gain into decibels.

where G is the power gain as a ratio and the logarithm is to the base 10. Thus, power gain of $G = 100$ converts to 20 dB, unity gain converts to 0 dB, and so on. An attenuator, for which the output power is smaller than the input power, has a negative decibel gain.

Recall that the overall gain for cascaded amplifiers is the product of the power gains of the individual amplifiers. When the gains are expressed in decibels, the gains of cascaded stages are added because of the properties of the logarithm. To illustrate this point, we have

$$G = G_1 G_2 \qquad (1.12)$$

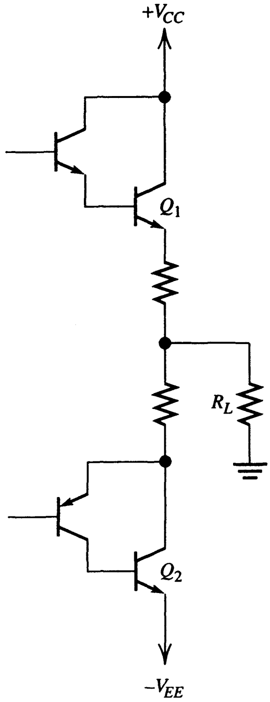


Figure 10.28 Pseudo complementary-symmetry class-B output stage that uses *npn* transistors for both of the main output devices (Q_1 and Q_2).

10.5 LINEAR VOLTAGE REGULATORS

Overview of Power-Supply Design

The function of a power supply is to deliver stable dc power that is free of noise and ac hum to the other parts of an electronic system.

The function of a power supply is to deliver stable dc power that is free of noise and ac hum to the other parts of an electronic system. Typically, the input to the power supply is the standard 60-Hz ac distribution voltage of (approximately) 120 V rms. However, particularly in mobile applications (automobiles, aircraft, etc.), the primary power source can be an ac voltage with different specifications, or it can be a dc voltage different in value from the desired output.

Several output voltages with different current capabilities may be required. For example, in a medium-size system incorporating both digital and analog circuits, +5 V with a current capability of 10 A and ±15 V with a capability of 1 A each are typical requirements.

... the power supply usually contains a **voltage regulator** that automatically adjusts the output voltage to maintain a nearly constant value, regardless of the input voltage and load current.

In many cases, the power supply must be designed to operate with a variable input voltage. For example, the equipment may be required to function properly with power-line voltages that are ±15% from the nominal value. Furthermore, the load current may vary, tending to change the output voltage of the supply. Therefore, the power supply usually contains a **voltage regulator** that automatically adjusts the output voltage to maintain a nearly constant value, regardless of the input voltage and load current.

Figure 10.29 shows the block diagram of a typical power supply. The transformer, rectifier, and filter capacitor convert the ac line voltage to an imperfect dc voltage v_C.

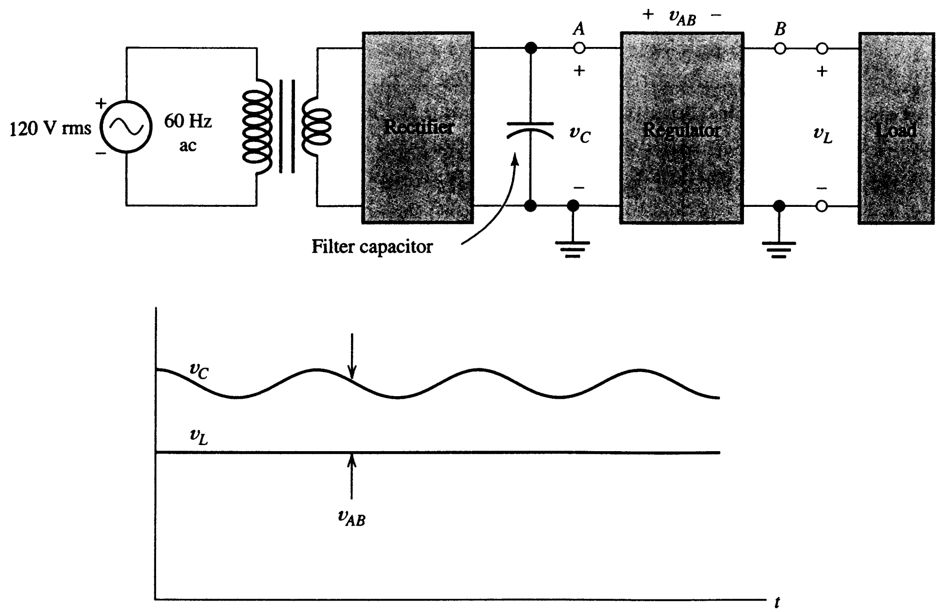


Figure 10.29 Line-operated power-supply block diagram.

This voltage contains an ac component known as **ripple**. Furthermore, v_C fluctuates due to changes in the line voltage and in load current.

The regulator divides the raw dc voltage v_C into two parts: a constant dc voltage v_L across the load and the remainder v_{AB} across the regulator.

Two basic approaches to voltage-regulator design are in common use. In a so-called **linear regulator**, BJTs (or FETs) control the flow of power to the load, and these devices are operated in their active region. When the load voltage becomes lower (or higher) than the desired value, the inputs to the devices are changed to increase (or decrease) the load voltage toward the desired value.

In a **switching regulator**, the devices act as switches that are either on or off. These switches deliver high-frequency pulses of power from the raw supply to energy storage elements (inductors or capacitors) that maintain a nearly constant load voltage. Typically, when the output voltage becomes lower than the desired value, the durations of the pulses are increased. The longer pulses deliver more power to the energy storage elements, thereby increasing the output voltage toward the desired value. Similarly, if the output voltage is too high, the pulse durations are reduced.

Two types of voltage regulators are the linear regulator and the switching regulator.

In general, switching power supplies are more efficient, smaller, and lighter in weight than linear power supplies having comparable output capability. However, linear power supplies are less complex and do not generate interference caused by switching transients (which can be a formidable problem when switching power supplies are used in weak-signal applications). We emphasize linear power supplies in this book.

As in power amplifiers, dissipation can be large in the devices used in power supplies. Therefore, consideration must be given to providing means for removing this heat so that the device temperatures do not become too high.

Often, in designing electronic systems, we resort to purchasing the required power supplies from a manufacturer that specializes in power supplies. Nevertheless, some knowledge of the internal operation and design trade-offs is useful in making a proper choice from a catalog. Furthermore, special-purpose applications arise for which a standard product is not available, and then custom design becomes a necessity.

Linear Voltage Regulators

The functional diagram of a linear regulator is shown in Figure 10.30. We will see that under proper conditions the load voltage v_L is nearly independent of both the load current and changes in the input voltage v_C.

The load voltage is sampled by a voltage divider consisting of R_1 and R_2. For ease of analysis, we neglect the input current of the differential amplifier. Thus, the voltage at the noninverting input of the amplifier is

$$v_2 = \frac{R_2}{R_1 + R_2} v_L = \beta v_L \tag{10.41}$$

in which we have defined the voltage-divider ratio

$$\beta = \frac{R_2}{R_1 + R_2} \tag{10.42}$$

The inverting input of the amplifier is connected to a dc reference voltage V_{ref}, which ideally should be free of ac hum and variations with temperature. In practice, the reference voltage is usually provided by a Zener diode.

The differential input voltage of the amplifier is

$$v_i = \beta v_L - V_{\text{ref}} \tag{10.43}$$

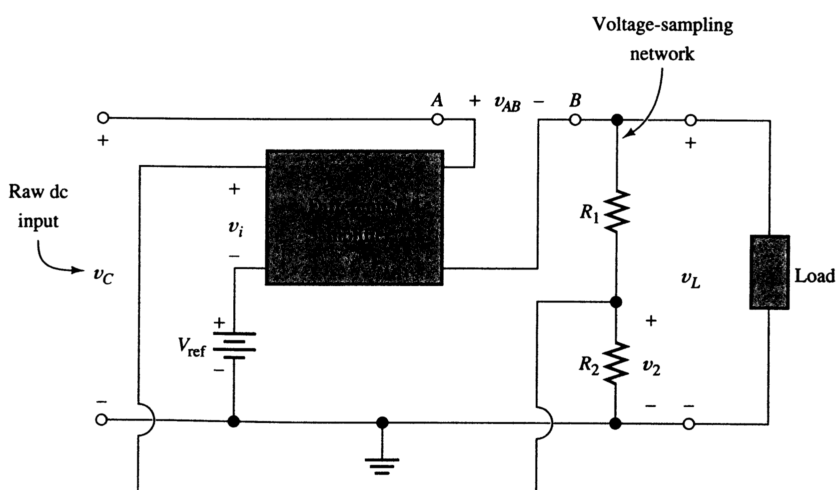


Figure 10.30 Linear series regulator.

We denote the differential voltage gain of the amplifier as A. Thus, the amplifier output voltage is

$$v_{AB} = Av_i \tag{10.44}$$

Using Equation (10.43) to substitute for v_i in Equation (10.44), we have

$$v_{AB} = A(\beta v_L - V_{\text{ref}}) \tag{10.45}$$

Referring to Figure 10.30 and writing a voltage equation, we obtain

$$v_C = v_{AB} + v_L \tag{10.46}$$

Using Equation (10.45) to substitute for v_{AB}, we get

$$v_C = A(\beta v_L - V_{\text{ref}}) + v_L \tag{10.47}$$

Solving Equation (10.47) for v_L, we obtain

$$v_L = \frac{v_C}{A\beta + 1} + \frac{AV_{\text{ref}}}{A\beta + 1} \tag{10.48}$$

If $A\beta$ is very large compared with unity, the first term on the right-hand side is negligible, and we have

$$v_L \cong \frac{V_{\text{ref}}}{\beta} = V_{\text{ref}} \frac{R_2}{R_1 + R_2} \tag{10.49}$$

Thus, given a high amplifier gain and a stable reference voltage V_{ref}, the load voltage is constant. To summarize, the important points in designing a regulator based on Figure 10.30 are to provide a stable voltage reference, a high amplifier gain, and a precise, stable voltage divider network.

To summarize, the important points in designing a regulator based on Figure 10.30 are to provide a stable voltage reference, a high amplifier gain, and a precise, stable voltage divider network.

The Voltage Regulator as a Negative-Feedback System

It is worthwhile to notice that the regulator shown in Figure 10.30 is an application of negative feedback. Suppose that the circuit is initially operating in equilibrium, and then the load begins to draw a larger current. The immediate effect of the higher load current is a reduction in the load voltage. This in turn reduces the input voltage to the differential amplifier, which then reduces the voltage drop v_{AB} across the regulator. The reduction of v_{AB} tends to increase the load voltage. Hence, changes in the load voltage are opposed by feedback through the amplifier.

Series versus Shunt Regulators

The regulator illustrated in Figure 10.30 is called a **series regulator** because the load voltage is controlled by the amplifier output, which is in series with the load. It is possible to design **shunt regulators**, in which the control elements are placed in parallel with the load. In a shunt regulator, if the load voltage is low, the control element responds by drawing less current. A simple shunt regulator circuit is shown in Figure 10.31. We considered this circuit in Section 3.7. Series regulators are used almost exclusively in medium- and high-power applications.

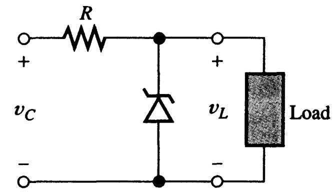


Figure 10.31 Simple shunt regulator circuit.

A Low-Power Example

Figure 10.32 depicts a low-power linear power supply. The circuit is not a good example of current design practice; instead, it has been designed to illustrate voltage-regulator principles using general-purpose devices. (The schematic is stored in the file named Fig10_32, which can be downloaded from the Website.)

The 32-V peak ac source shown in the figure corresponds to the open-circuit voltage of the transformer secondary, and R_t is the net winding resistance reflected to the secondary. (We will have more to say about transformers and their ratings later.)

We have chosen to use a 1N4002 rectifier diode, which is a readily available inexpensive rectifier. In this example, we have chosen a half-wave rectifier circuit for simplicity, but we will see later that better performance can be obtained with full-wave circuits.

The capacitor C_f is charged once each cycle by current flowing through the diode D_1. Between positive peaks of the ac input, the capacitor supplies current to the load through the regulator. As a result, the capacitor voltage displays 60-Hz ripple. Figure 10.33 shows the voltage across the capacitor and the regulated load voltage, assuming that the ac input is turned on at $t = 0$. After a few cycles the capacitor voltage reaches a steady-state condition, with several volts of peak-to-peak ripple. The load voltage is nearly constant at approximately 15 V.

The resistor R_r supplies current to D_2, which provides the reference voltage to the noninverting op-amp input. The resulting reference voltage is approximately 4.4 V and contains only a few millivolts of ac ripple.

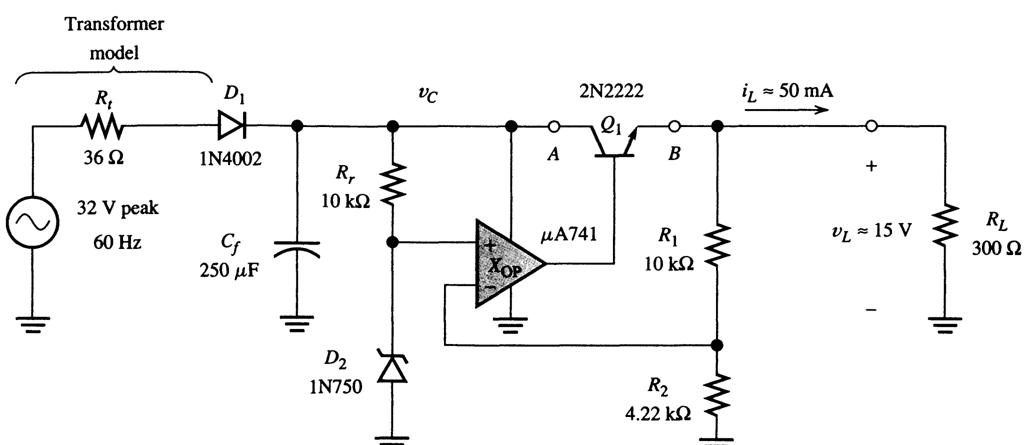


Figure 10.32 Example power supply.

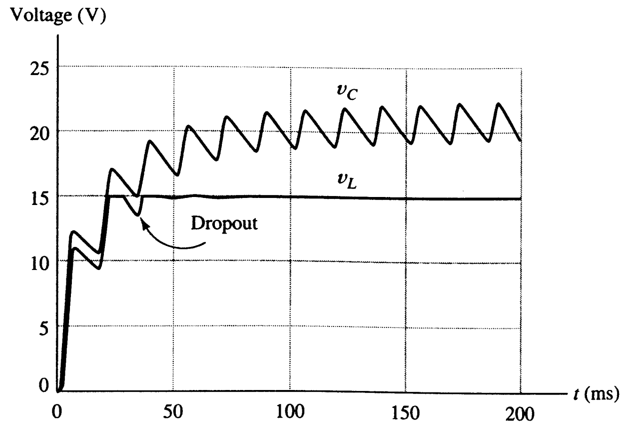


Figure 10.33 Voltage waveforms for the power supply of Figure 10.32.

The differential amplifier function is provided by the op amp and transistor Q_1. This transistor is called a **series pass transistor**, because it is in series with the load and the load current must pass through it. (The transistor is needed because the load current exceeds the capability of the op amp.)

When the output voltage of the op amp increases in value, the base current of Q_1 increases, and the collector-to-emitter voltage v_{AB} decreases in value. Thus, Q_1 acts as an inverting amplifier. Therefore, the *inverting* input of the op amp plays the role of the *noninverting* input of the overall amplifier (which is composed of the op amp cascaded with the series pass transistor Q_1). If we compare the figures, we see that the inverting terminal of the op amp in Figure 10.32 corresponds to the noninverting input of the amplifier in Figure 10.30.

Resistors R_1 and R_2 form the voltage-sampling network. The values have been selected so that the output voltage is nearly 15 V. In practice, the voltage of the Zener diode displays unit-to-unit variations. Then, if a precise output voltage is required, the sampling network must be adjustable. Finally, R_L simulates the useful load.

Dropout Voltage

Linear regulator circuits require a sufficiently large input–output differential v_{AB} for proper operation. The minimum differential is known as the **dropout voltage**. For example, in the circuit shown in Figure 10.32, the maximum op-amp output voltage is approximately 0.4 V less than the voltage applied to the positive power terminal of the op amp. (Actually, the μA741 is not *guaranteed* to produce an output this close to its positive supply voltage. The PSpice model is representative of a typical unit instead of a worst-case unit.) Furthermore, for the transistor to be in the active region, the base terminal must be approximately 0.7 V higher than the emitter terminal. Thus, the dropout voltage for the circuit is approximately $0.4 + 0.7 = 1.1$ V.

We must ensure that the minimum value of the raw dc voltage is greater than the sum of the desired load voltage and the dropout voltage of the regulator. Otherwise the regulator is unable to reduce v_{AB} sufficiently to maintain v_L constant. An example of dropout is illustrated in Figure 10.33.

The dropout voltage of a linear series regulator is the minimum allowed difference between the input voltage and the load voltage.

The raw dc voltage v_C input to the regulator must be sufficiently high to avoid dropout under normal operating conditions. However, we should not design for raw dc input voltages that are much higher than necessary, because the load current must flow through the voltage drop v_{AB}, resulting in wasted power that is dissipated as heat in the regulator. Thus, we design the circuit so that the input voltage to the regulator is slightly greater than the sum of the dropout voltage and the desired output voltage under worst-case conditions.

Diode Current Waveforms

The current through the diode D_1 for the circuit of Figure 10.32 is illustrated in Figure 10.34. The current flows in pulses when the diode is forward biased by the positive peaks of the ac input voltage.

Because the capacitor is uncharged to begin with, the initial **surge** is larger than the steady-state pulse amplitudes. We must select a diode that is rated to withstand this initial current surge. The 1N4002 diode is rated for a surge current of 30 A for one cycle at 60 Hz, so it operates well within its ratings.

In steady state, the average current through the diode is equal to the sum of the load current (50 mA), the current taken by the sampling network (about 1 mA), the current used by the voltage reference (about 1 mA), and the supply current for the op amp (about 4 mA). Hence, the average diode current is about 56 mA. However, because the diode current flows in pulses, the peak value of the pulses is approximately 300 mA.

In rectifiers with capacitive filters, the peak diode current is many times higher than the load current. Of course, we must allow for this in selecting the diode.

The diode current also flows through the internal resistance of the source (i.e., the resistance of the transformer windings). Therefore, some power is dissipated as heat in the transformer. The power dissipated in the transformer depends on the rms value of the current. Keep in mind that, because the current waveform is not a sinusoid, we cannot use the familiar factor of 0.707 to convert from peak value to rms value. (Some SPICE programs provide commands that can be used to compute the average and true rms values of a waveform.)

The rms current in the transformer winding is several times larger than the dc load current (118 mA versus 50 mA in this case). Thus, in power-supply design, the rms current rating of the transformer must be higher than the dc load current.

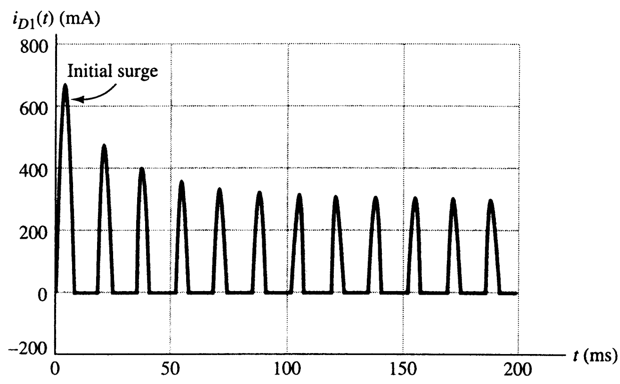


Figure 10.34 Diode current for the power supply of Figure 10.32.

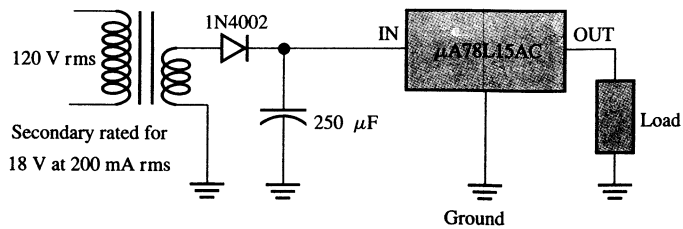


Figure 10.35 Improved 15-V 50-mA power supply (compare to Figure 10.32).

Integrated-Circuit Voltage Regulators

In practice, we seldom design voltage regulators using general-purpose parts. Instead, complete regulators are available in the form of integrated circuits. For example, the circuit of Figure 10.32 can be redesigned so that it uses an LM78L15AC regulator IC, which is available from National Semiconductor. The redesigned circuit is shown in Figure 10.35. The parts count has been drastically reduced, resulting in a circuit that is more economical.

The LM78LXX regulator is available for nominal output voltages of 2.6, 5, 6.2, 8, 9, 10, 12, and 15 V. (The last two digits of the part number indicate the voltage; for example, an LM78L05 is a 5-V regulator.) Versions having output voltage tolerances of either $\pm5\%$ or $\pm10\%$ are available. These regulators are suitable for load currents up to 100 mA. Dropout voltages range from 2 to 2.5 V, depending on the output voltage rating.

Manufacturers offer many other regulator ICs suitable for higher current levels and for negative output voltages. Often, external power transistors are used with regulator ICs for high-power designs.

EXERCISE

10.5 Suppose that the load of Figure 10.32 becomes an open circuit. What will happen to the voltage waveforms v_C and v_L?

Answer With very little current drawn from the rectifier, v_C rises nearly to the peak value of the ac source. Thus, we estimate that v_C will become approximately 30 V. The regulator holds the load voltage constant at 15 V. Of course, you can check your estimates by using SPICE.

EXERCISE

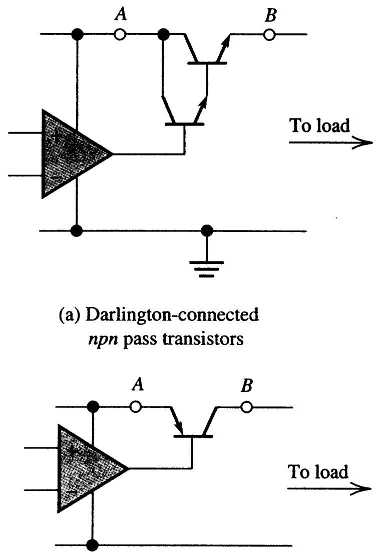
10.6 Modify component values in the power-supply circuit of Figure 10.32 so that the output voltage is 10-V dc. Check your redesign by using SPICE.

Answer Many correct answers exist. One possibility is to change the value of R_2 to $8\,k\Omega$. (We assume that R_2 is adjustable, so it need not be a standard value.)

EXERCISE

10.7 Consider the pass-transistor configurations shown in Figure 10.36. Suppose that the op amp is capable of a maximum output voltage that is 0.5 V less than its positive supply voltage (which is the input voltage to the regulator). Assume base-to-emitter voltages of 0.7 V in magnitude in the active region. Also, assume collector-to-emitter saturation voltages of 0.2 V in magnitude. Find the dropout voltage for each configuration.

Answer (a) $V_{dropout} \cong 1.9\,V$; (b) $V_{dropout} \cong 0.2\,V$.



(a) Darlington-connected *npn* pass transistors

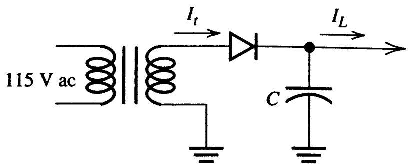
(b) *pnp* pass transistor

Figure 10.36 Alternative pass-transistor configurations.

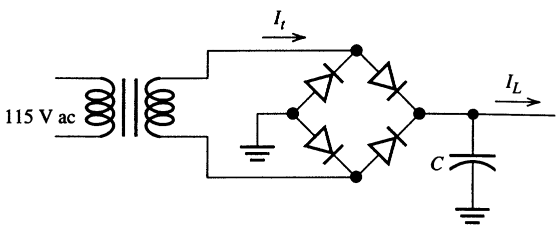
10.6 LINEAR-POWER-SUPPLY DESIGN

Figure 10.37 shows the rectifier circuits most commonly employed in modern power-supply designs. (In the past, rectifiers that used inductors to help reduce ripple were common. However, electronic regulators have eliminated the necessity for inductors.) We considered the basic operation of several of these circuits in Section 3.4. On the peak of the ac input, the diode(s) conducts charging the capacitors. Between peaks, the capacitor continues to supply current to the load.

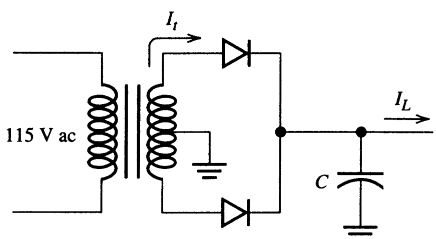
In the half-wave circuit, the capacitor is charged once per cycle. On the other hand, in full-wave circuits, the capacitors are charged twice per cycle.



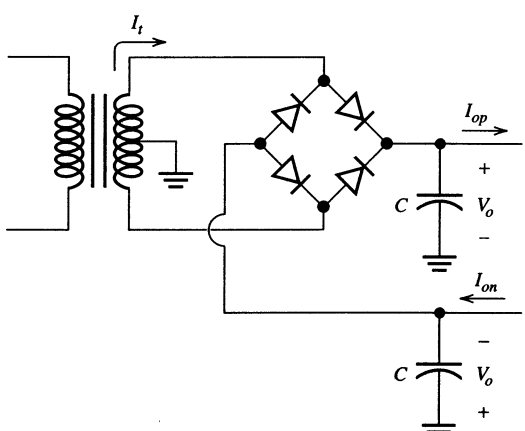
(a) Half-wave circuit: $I_{t,\mathrm{rms}} \cong 3.0 I_{L,\mathrm{avg}}$



(b) Full-wave bridge circuit: $I_{t,\mathrm{rms}} \cong 1.8 I_{L,\mathrm{avg}}$



(c) Full-wave center-tapped circuit: $I_{t,\mathrm{rms}} \cong 1.2 I_{L,\mathrm{avg}}$



(d) Full-wave complementary-output rectifier:
$I_{t,\mathrm{rms}} \cong 1.2\sqrt{I_{op,\mathrm{avg}}^2 + I_{on,\mathrm{avg}}^2}$

Figure 10.37 Rectifier circuits.

Transformers

The functions of the transformer are to provide the appropriate ac voltage level for the rectifier and to isolate the load from the ac power line. The isolation function of the transformer is important. By proper use of a transformer, the load is not connected directly to either side of the power line. This lends a measure of safety for those working with the circuit. Sometimes, in the interest of economy, power supplies have been designed without transformers—particularly in radios and in television receivers. In such circuits, the metal chassis can be connected to the "hot" side of the power line. *Then, if one is in contact with power-system ground, which is often the case, touching the chassis (which is intended to be inside an insulating enclosure) can be fatal.*

Isolation is essential for circuits (oscilloscopes and other laboratory instrumentation, for example) that are intended to be interconnected with other equipment having a common ground.

Besides having the proper voltage rating, the transformer must have a proper current rating. Ohmic loss in the transformer windings leads to increased temperature. If the actual current exceeds the rated value, the lifetime of the insulation is drastically reduced. Furthermore, a transformer operated in excess of its rated current is a potential fire hazard.

Of course, it is the rms value of the current in a transformer winding that determines the amount of heating. Because the current flows in short-duration, high-amplitude pulses, the rms value is larger than the average load current. An estimate of the rms secondary-winding current in terms of the dc load current is given in Figure 10.37 for each rectifier shown. The estimates apply for typical designs. Depending on the circuit parameters, the rms current can be higher than the estimates, so they should be used with caution. The rms current becomes higher for lower transformer resistance, lower diode resistance, and larger filter capacitance.

Because of winding resistance, the average secondary voltage decreases as increased current is drawn from the transformer. The regulation of a transformer is defined as

$$\text{Regulation} = \frac{V_{oc} - V_{fl}}{V_{fl}} \times 100\% \qquad (10.50)$$

where V_{oc} is the *open-circuit* secondary voltage and V_{fl} is the *full-load* secondary voltage with a resistive load drawing rated current. Typical transformers found in electronic power supplies have regulations ranging from 5% to 20%. The voltage, current, and regulation ratings can be used to find the Thévenin equivalent for the transformer.

Example 10.7 Transformer Equivalent Circuit

A certain transformer is rated for a secondary voltage of 12 V rms at a secondary current of 2 A rms. The regulation rating is 10%. Find the Thévenin equivalent for the transformer secondary.

SOLUTION The full-load voltage is $V_{fl} = 12$ V and the regulation rating is 10%. Substituting these values into Equation (10.50), we have

$$\frac{V_{oc} - 12}{12} \times 100\% = 10\%$$

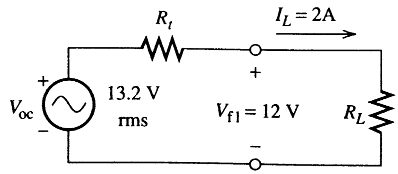


Figure 10.38 Thévenin equivalent circuit for transformer secondary. (See Example 10.7.)

Solving the equation for the open-circuit secondary voltage, we obtain

$$V_{oc} = 13.2\,\mathrm{V}$$

The Thévenin model for the transformer is shown in Figure 10.38. For a load current of 2 A, the drop across the Thévenin resistance is $V_{oc} - V_{fl} = 1.2\,\mathrm{V}$. Thus, the Thévenin resistance is

$$R_t = \frac{1.2}{2} = 0.6\,\Omega$$

❑

Actually, the Thévenin impedance of a transformer is not purely resistive—instead, it consists partly of inductive reactance. However, complete data are often not readily available for a given transformer. The simple resistive Thévenin model is sufficiently accurate for most designs.

Diodes

The function of diodes is to allow current to flow only in one direction—that which charges the filter capacitor. The diode ratings must be higher than the peak forward current and peak inverse voltage (PIV) expected in the circuit. If the forward current rating of a diode is exceeded, the diode overheats, leading to failure. If the PIV rating is exceeded, the diode may break down, causing large reverse currents to flow, destroying other circuit components.

Filter Capacitors

The function of a capacitor is to store the charge pulses that flow through the diodes. A large capacitance discharges only slightly between current pulses. Thus, the capacitor maintains a nearly constant output voltage.

In Section 3.4, we found that the capacitance values required are given by Equations (3.4) and (3.6), which are repeated here for convenience:

$$C = \frac{I_L T}{V_r} \quad \text{(for the half-wave circuit)}$$

$$C = \frac{I_L T}{2V_r} \quad \text{(for full-wave circuits)}$$

In both equations, T is the period of the ac input (usually, $T = 1/60\,\text{s}$), I_L is the dc load current, and V_r is the peak-to-peak ripple voltage.

Actually, these formulas overestimate the capacitance values required, because, in deriving them, we assumed that the charging interval is negligible in duration compared with the discharge interval. However, capacitors often have loose tolerances, such as -50% to $+100\%$. Therefore, a precise determination of the capacitance value required is moot.

It is not good practice to design for extremely small amounts of ripple by using very large capacitors, because this shortens the conduction interval and increases the peak current. High-amplitude current pulses create excessive heating in the diodes and transformer windings, so their current and power ratings must be larger. Hence, obtaining low ripple by using large filter capacitors is uneconomical. Instead, we design for several volts of peak-to-peak ripple and depend on the regulator to provide a constant load voltage.

Commonly, the rather large-valued capacitors used in power supplies are **electrolytic** types for which the dc voltage must be applied with a particular polarity. Electrolytic capacitors are marked with the proper polarity, and they soon fail if connected with incorrect polarity.

We must pay attention to the maximum voltage rating of the capacitor. The peak voltage under worst-case conditions (the highest line voltage and no load current) must not exceed the maximum voltage rating.

The dc current through any capacitor is (ideally) zero. However, considerable ac current can flow, and this current results in power dissipation in the (small) resistance of the conductors that make up the capacitor plates. If this heating is excessive, the capacitor can fail—sometimes with a loud bang when the pressure of a boiling electrolyte causes the case to rupture. We should check our designs to make sure that the rms ac current through the filter capacitor is within its ratings.

A Design Example

The design of a linear power supply typically consists of selecting a voltage regulator IC and a circuit configuration from the possibilities shown in Figure 10.37 on page 709. Then, each of the components is specified and care is taken to ensure that they all operate within their ratings.

The design of the raw power supply amounts to selecting a circuit configuration and component values that produce the required dc output voltage and current. Of course, we must ensure that all of the components operate within their ratings. In a practical design, we would consider many circuit configurations and combinations of component values in an attempt to find the most economical solution.

Example 10.8 Design of a 5-V, 1-A Power Supply

Suppose that we want to design a 5-V dc supply capable of delivering 1 A of current. The supply is required to operate properly for line voltages ranging from 105 V rms to 130 V rms. The regulator to be used has a $\pm 10\%$ tolerance for the output voltage and a maximum dropout voltage of 2.5 V. Thus, the minimum allowed input to the regulator is $2.5 + 5 \times 1.1 = 8\,\text{V}$. Design a rectifier for this power supply.

SOLUTION First, we select a circuit configuration. For purposes of illustration, we choose the full-wave center-tapped circuit shown in Figure 10.37c. (We leave consideration of the other configurations for the exercises.)

As indicated in Figure 10.37c, a starting estimate for the rms secondary current of the transformer is

$$I_{t,\,\mathrm{rms}} = 1.2 I_{L,\,\mathrm{avg}}$$

Because the specifications call for a load current of 1 A, we have a preliminary value of $I_{t,\,\mathrm{rms}} = 1.2\,\mathrm{A}$. We should design with some safety margin, so we will consider only transformers with a current rating of at least 1.5 A.

Next, we select the type of diode. After some search through manufacturers' data sheets for rectifier diodes, we find the 1N4001-through-1N4007 series. The diodes have identical ratings, except for the peak inverse voltage, which ranges from 50 V for the 1N4001 to 1000 V for the 1N4007. In this relatively low-voltage circuit, even the 1N4001 is more than sufficient with regard to the PIV rating. These diodes are rated for an average forward current of 1 A when they are used in a half-wave rectifier with a resistive load. In our circuit, the average forward current of each diode is 0.5 A. (There are two diodes.) However, the diodes deliver current to a filter capacitor rather than to a resistive load, so we can expect peak currents several times larger than the average. This is because the charge delivered by the capacitor to the load must be replenished during a short-duration pulse of diode current. Therefore, even though the average current in our application is half of the rated value, there is some cause for concern because of the potentially higher peak currents.

The preceding scenario is typical of situations that occur in design: Component ratings are given for a test circuit different from the circuit being designed. We must then use engineering judgment, make measurements on the preliminary design, or request more information from the manufacturer of the device to resolve uncertainty about its suitability for use in our design. In this case, our initial judgment is that the 1N4001 diode is suitable.

Next, we estimate the voltage rating of the secondary winding. Suppose that we decide to design for a peak-to-peak ripple voltage of $V_r = 2\,\mathrm{V}$. This choice is based on experience, and it is arbitrary to some degree. If we choose V_r very small, say, a tenth of a volt, a larger, more expensive filter capacitor is required, and the peak current may become excessive. On the other hand, too large a value, say, $V_r = 10\,\mathrm{V}$, leads to an inefficient power supply because the average voltage into the regulator must be higher.

Frequently, engineering choices are based on past experience with similar circuits. When we lack experience, our initial choices may be poor, but this becomes apparent as the design develops, and we learn to make better choices. When in doubt, pick a value and proceed. Just make sure you have a clear understanding of the consequences of each decision by the end of the design process.

Frequently, engineering choices are based on past experience with similar circuits. When we lack experience, our initial choices may be poor, but this becomes apparent as the design develops, and we learn to make better choices.

Experience indicates that the peak diode current will be 5 to 20 times higher than the average load current in a capacitive input rectifier. Therefore, we expect peak diode currents of 5 to 20 A in this case. The data sheet for the 1N4001 diode shows that we should expect a forward voltage of 1.5 V for currents of this magnitude.

In addition, our judgment is to allow for a 1-V drop across the transformer resistance. (For transformers operated close to their ratings, start with an estimate for the transformer resistance drop of 10% to 20% of the output voltage of the rectifier.)

Finally, we should allow some design margin. Therefore, we will design for a minimum voltage of 9 V rather than 8 V. Thus, we estimate the required peak open-circuit (Thévenin) voltage of the secondary winding to be

$$V_{\text{oc, peak}} = V_{L,\text{min}} + V_{\text{diode}} + V_r + V_{\text{drop}}$$

$$V_{\text{oc, peak}} = 9 + 1.5 + 2 + 1 = 13.5\text{ V}$$

Because the circuit is required to function with ac line voltages ranging from 105 V to 130 V, we need to specify a transformer having a peak open-circuit secondary voltage of 13.5 V for a line voltage of 105 V. Therefore, the peak open-circuit voltage for a line voltage of 120 V is

$$V_{\text{oc, peak}} = 13.5 \times \frac{120}{105} = 15.4\text{ V}$$

The rms value of the open-circuit secondary voltage is

$$V_{\text{oc, rms}} = V_{\text{oc, peak}} \times 0.707 \cong 10.9\text{ V}$$

Assuming a regulation of 10%, the minimum secondary voltage rating becomes $V_{\text{fl}} \cong 9.9$ V rms for each half of the winding (19.8 V, center tapped).

In sum, the transformer secondary should be rated for 1.5 A rms and (at least) 19.8 V, center tapped. Now we consult manufacturers' catalogs to find a suitable transformer. Often, we will not find a standard product with ratings that exactly match our requirements. Then, we must select a unit that has higher ratings or try to obtain a custom transformer. Usually, a custom transformer is justified only if a very large number of transformers are required or if the specifications cannot be satisfied with a standard model. Suppose that this time we find a transformer with the following ratings:

- The secondary voltage is 20 V, center tapped (for a line voltage of 120 V and with a resistive load that is drawing rated secondary current).
- The secondary current rating is 1.5 A rms.
- The regulation is 10%.

Proceeding as in Example 10.6, we find that each half of the secondary winding can be represented as an 11-V-rms (or $11 \times \sqrt{2} = 15.6$ V peak) ac voltage source in series with a Thévenin resistance of 0.67 Ω. For a line voltage of 105 V rms, the peak secondary voltage is reduced to $15.6 \times 105/120 = 13.6$ V.

Next, we compute the value of the filter capacitance required. Recall that we decided to design for a peak-to-peak ripple voltage of $V_r = 2$ V. Thus, we have

$$C = \frac{I_L T}{2V_r} = \frac{1 \times 1/60}{2 \times 2} = 4167\ \mu\text{F}$$

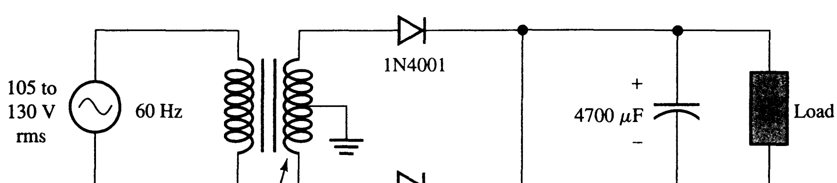
Now we must consider the voltage rating of the capacitor. Under high line voltage conditions with no load current, we can expect a capacitor voltage of (approximately) $15.6 \times (130/120) = 16.9$ V. Suppose that, after consulting manufacturers' catalogs, we decide to use a 4700-μF electrolytic capacitor having a tolerance of −10% to +50% and a voltage rating of 20 V. (Because the capacitor is an electrolytic type, we must take care that the voltage is applied with the correct polarity.)

We must also consider the current rating of the capacitor: If the ac current in the capacitor is too high, overheating and premature failure can result. Suppose that this particular capacitor is rated for a maximum ac current of 2 A rms.

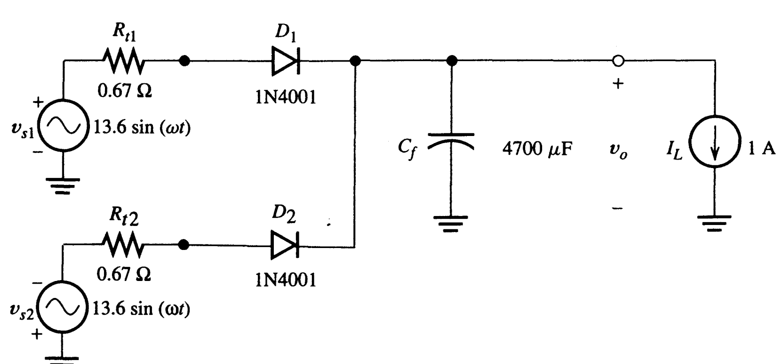
Figure 10.39a shows the actual rectifier circuit diagram. The load for the rectifier consists of a voltage regulator that maintains a constant voltage to the useful load. Thus, we expect that the current drawn from the rectifier is constant at 1 A.

Figure 10.39b depicts the circuit model used for the SPICE simulation. The load is represented as a 1-A dc current source, and the secondary windings of the transformer are represented by their Thévenin equivalent circuits. We have used the secondary voltage corresponding to a line voltage of 105 V rms, because we want to check the minimum output voltage under low-line conditions.

Figure 10.40 shows the rectifier output voltage versus time. After a few cycles, it reaches steady state. The minimum voltage is slightly greater than the design value of 9 V. The peak-to-peak ripple voltage is a bit less than the value for which we designed our power supply, namely, 2 V.



(a) Actual circuit



(b) Circuit model used for PSpice analysis

Figure 10.39 Rectifier designed in Example 10.7.

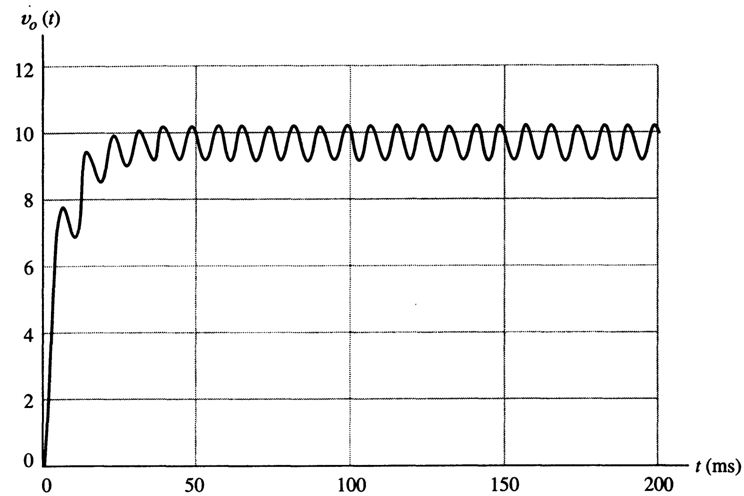


Figure 10.40 Rectifier output voltage.

Figure 10.41 shows the current through diode D_1. Notice that the first current pulse is much higher than the succeeding pulses. This is due to the fact that the capacitor voltage is initially zero, so the first cycle must deliver much more charge to the capacitor than succeeding cycles do. Reference to the data sheet for the 1N4001 shows that the diode is rated for a surge current of 30 A. Thus, the 10.5-A peak surge that we observe is well within the ratings of the diode. Using Probe, we also determine that the rms current through the capacitor is 1.38 A, which is within the capacitor ratings.

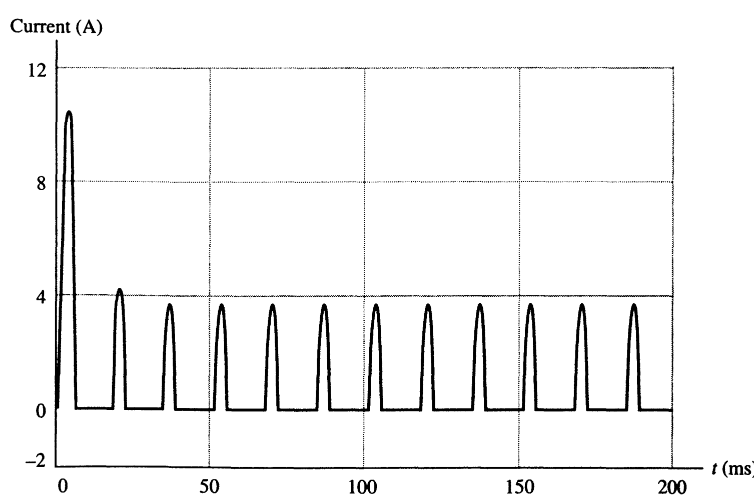


Figure 10.41 Current through diode D_1.

If desired, additional checks of the circuit waveforms can be obtained for high line-voltage conditions and for load currents ranging from zero to 1 A. It will be found that the circuit components are within their ratings for line voltages in the design range. ❑

EXERCISE

10.8 Repeat Example 10.7, using the full-wave bridge circuit illustrated in Figure 10.37b. Select parts from the following list:

- 1N4002 diodes.
- Transformers with 10% regulation, $I_{fl} = 1\,\text{A}, 2\,\text{A}, 3\,\text{A}$, etc., and $V_{fl} = 2\,\text{V}$, $4\,\text{V}, 6\,\text{V}$, etc. The voltage rating is for a line voltage of 120 V rms.
- Electrolytic capacitors of 4700 μF −10% to +50% rated for 25 V and 3 A rms.

Use a SPICE program to verify that the minimum voltage is higher than the specified minimum of 9 V. Also, verify that the transformer and capacitor are operated within their ratings. Find the average power dissipated in each diode.

Answer See Figure 10.42. Using SPICE, we find that the secondary current is approximately 2.6 A rms, the capacitor current is approximately 2.25 A rms, and the minimum load voltage is 9.5 V.

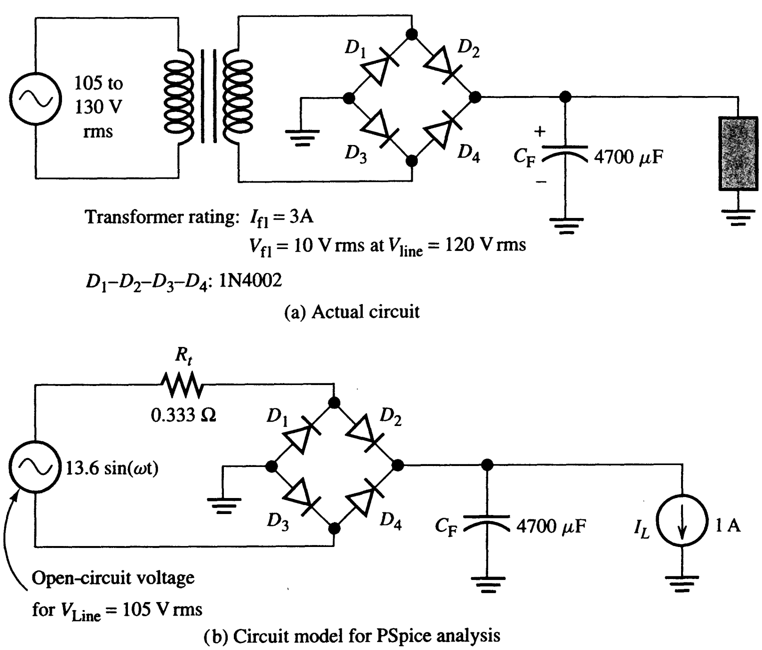


Figure 10.42 Answer for Exercise 10.8.

Thermal Design Considerations

We continue the design started in Example 10.8, including the thermal aspects of the design.

Example 10.9 Thermal Design for a Power Supply

Select a 10%-tolerance 5-V regulator and heat sink to be used with the power supply designed in Example 10.8. The maximum ambient temperature is 50°C. The maximum load current is 1 A.

SOLUTION First, we estimate the maximum power dissipated in the regulator. For this estimate, we should consider high line-voltage conditions and minimum output voltage, because this maximizes the input–output voltage differential and, therefore, the power dissipation of the regulator. We anticipate using a series regulator for which dissipation is highest under a full-load current.

The power supply is illustrated in Figure 10.39. Recall that the 1-A current source shown in Figure 10.39b represents the voltage regulator and the useful load. We want to find the maximum average power delivered to this current source. In Example 10.8, we selected a transformer with a peak open-circuit secondary voltage of 15.6 V at a nominal line voltage of 120 V rms. Under high line-voltage conditions (130 V rms), the open-circuit secondary voltage is

$$V_{\text{oc,max}} = 15.6 \times \frac{130}{120} = 16.9\,\text{V}$$

In Example 10.8, we used SPICE to simulate the circuit under low line-voltage conditions. Now if we change the voltage value to 16.9 V and simulate the circuit again, we find that the average voltage at the input to the regulator is approximately 12.8 V. Thus, the average power supplied to the regulator input is $P_{\text{in}} = 12.8\,\text{V} \times 1\,\text{A} = 12.8\,\text{W}$. However, for the minimum load voltage, the useful load power is $P_o = 4.5\,\text{V} \times 1\,\text{A} = 4.5\,\text{W}$. Consequently, the maximum power dissipated in the regulator is $P_D = P_{\text{in}} - P_o = 8.3\,\text{W}$.

Consequently, we must select a regulator and heat sink for which the junction temperature does not exceed $T_{J\,\text{max}}$ for $P_D = 8.3\,\text{W}$ and $T_A = 50°\text{C}$. Initially, we assume that $T_{J\,\text{max}} = 150°\text{C}$, which is a typical value for voltage regulator ICs. Then we can compute the maximum allowable junction-to-ambient thermal resistance:

$$\theta_{JA\,\text{max}} = \frac{T_{J\,\text{max}} - T_{A\,\text{max}}}{P_{D\,\text{max}}} = \frac{150 - 50}{8.3} = 12.0°\text{C/W}$$

Certainly, we must select a regulator for which θ_{JC} is considerably less than $\theta_{JA\,\text{max}}$.

One possibility is the LM7805 model, packaged in a TO-220AB case. The power-derating curve included in the data sheet for this device yields $\theta_{JC} = 4°\text{C/W}$. (This is the reciprocal of the slope of the case-temperature dissipation-derating curve.)

The case is connected to the common terminal. Therefore, we can bolt the regulator directly to the heat sink without insulating washers, and, based on

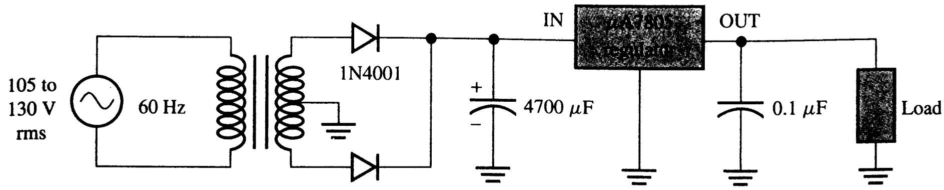


Figure 10.43 5-V, 1-A power supply designed in Examples 10.8 and 10.9.

experience, we can expect that $\theta_{CS} \cong 0.5°\text{C/W}$. Now the maximum thermal resistance allowed for the heat sink can be found:

$$\theta_{SA\,\text{max}} = \theta_{JA\,\text{max}} - \theta_{JC} - \theta_{CS} = 12.0 - 4 - 0.5 = 7.5°\text{C/W}$$

Next, we consult catalogs of heat-sink manufacturers to find a heat sink that meets this requirement. Many units are available, and we can make a choice based on other requirements, such as physical dimensions. Good design dictates some margin, so we should select a sink with θ_{SA} less than the maximum allowed.

Because the μA7805 regulator has internal thermal and short-circuit protection, it shuts down if the junction temperature becomes too high. Furthermore, under short-circuit conditions, the output current is limited to 0.75 A.

The manufacturer recommends paralleling a 0.1-μF capacitor with the load. The complete circuit is illustrated in Figure 10.43.

❑

As a final comment about the last example, we point out that in the process of delivering 4.5 W of useful power to the load, 8.3 W is dissipated as heat in the regulator. Additional heat is dissipated in the diodes and transformer. Thus, the efficiency of the power supply is considerably less than 50%. This is not unusual for power supplies that use linear regulators—particularly if the output voltage is fairly low, as it is in this case.

SUMMARY

- In designing circuits, we must consider their thermal characteristics to ensure that the junction temperatures of the active devices do not exceed their maximum ratings. By selecting a suitable combination of device, mounting method, and heat sink, we design for a sufficiently low case-to-ambient thermal resistance

$$\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA}$$

- Increased temperature of a BJT leads to higher β, higher leakage current I_{CBO}, and lower V_{BE}. All of these changes tend to increase the operating current in most circuits.
- Thermal runaway is a condition in which a higher temperature leads to a higher device current and increased power dissipation, which in turn increases the temperature still further. In poorly designed circuits, this process ends in the destruction of the device.