15

Power Supplies (Voltage Regulators)

CHAPTER OBJECTIVES

- How power supply circuits operate
- Operation of RC filters
- Discrete voltage regulator operation
- About practical IC voltage regulators

15.1 INTRODUCTION

Chapter 15 introduces the operation of power supply circuits built using filters, rectifiers, and then voltage regulators. (Refer to Chapter 2 for the initial description of diode rectifier circuits.) Starting with an ac voltage, we obtain a steady dc voltage by rectifying the ac voltage, then filtering to a dc level, and, finally, regulating to obtain a desired fixed dc voltage. The regulation is usually obtained from an IC voltage regulator unit, which takes a dc voltage and provides a somewhat lower dc voltage, which remains the same even if the input dc voltage varies or the output load connected to the dc voltage changes.

A block diagram containing the parts of a typical power supply and the voltage at various points in the unit is shown in Fig. 15.1. The ac voltage, typically 120 V rms, is connected to a transformer, which steps that ac voltage down to the level for the desired dc output. A diode rectifier then provides a full-wave rectified voltage, which is initially filtered by a basic capacitor filter to produce a dc voltage. This resulting dc voltage usually has some ripple or ac voltage variation. A regulator circuit can use this dc input to provide a dc voltage that not only has much less ripple voltage, but also remains at the same dc value even if the input dc voltage varies somewhat or the load connected to the output dc voltage changes. This voltage regulation is usually obtained using one of a number of popular voltage regulator IC units.

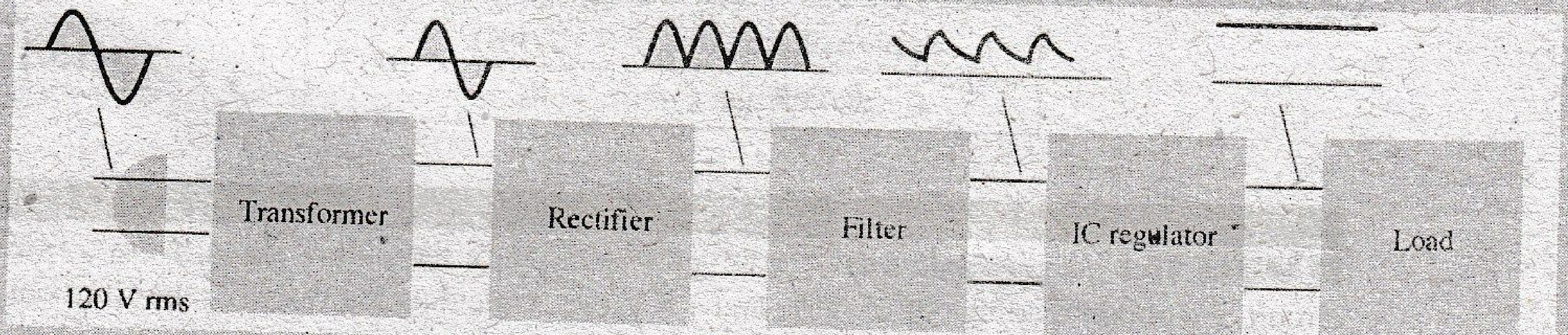


FIG. 15.1
Block diagram showing parts of a power supply.

15.2 GENERAL FILTER CONSIDERATIONS

A rectifier circuit is necessary to convert a signal having zero average value into one that has a nonzero average. The output resulting from a rectifier is a pulsating dc voltage and not yet suitable as a battery replacement. Such a voltage could be used in, say, a battery charger, where the average dc voltage is large enough to provide a charging current for the battery. For dc supply voltages, such as those used in a radio, stereo system, computer, and so on, the pulsating dc voltage from a rectifier is not good enough. A filter circuit is necessary to provide a steadier dc voltage.

Filter Voltage Regulation and Ripple Voltage

Before going into the details of a filter circuit, it would be appropriate to consider the usual methods of rating filter circuits so that we can compare a circuit's effectiveness as a filter. Figure 15.2 shows a typical filter output voltage, which will be used to define some of the signal factors. The filtered output of Fig. 15.2 has a dc value and some ac variation (ripple). Although a battery has essentially a constant or dc output voltage, the dc voltage derived from an ac source signal by rectifying and filtering will have some ac variation (ripple). The smaller the ac variation with respect to the dc level, the better is the filter circuit's operation.

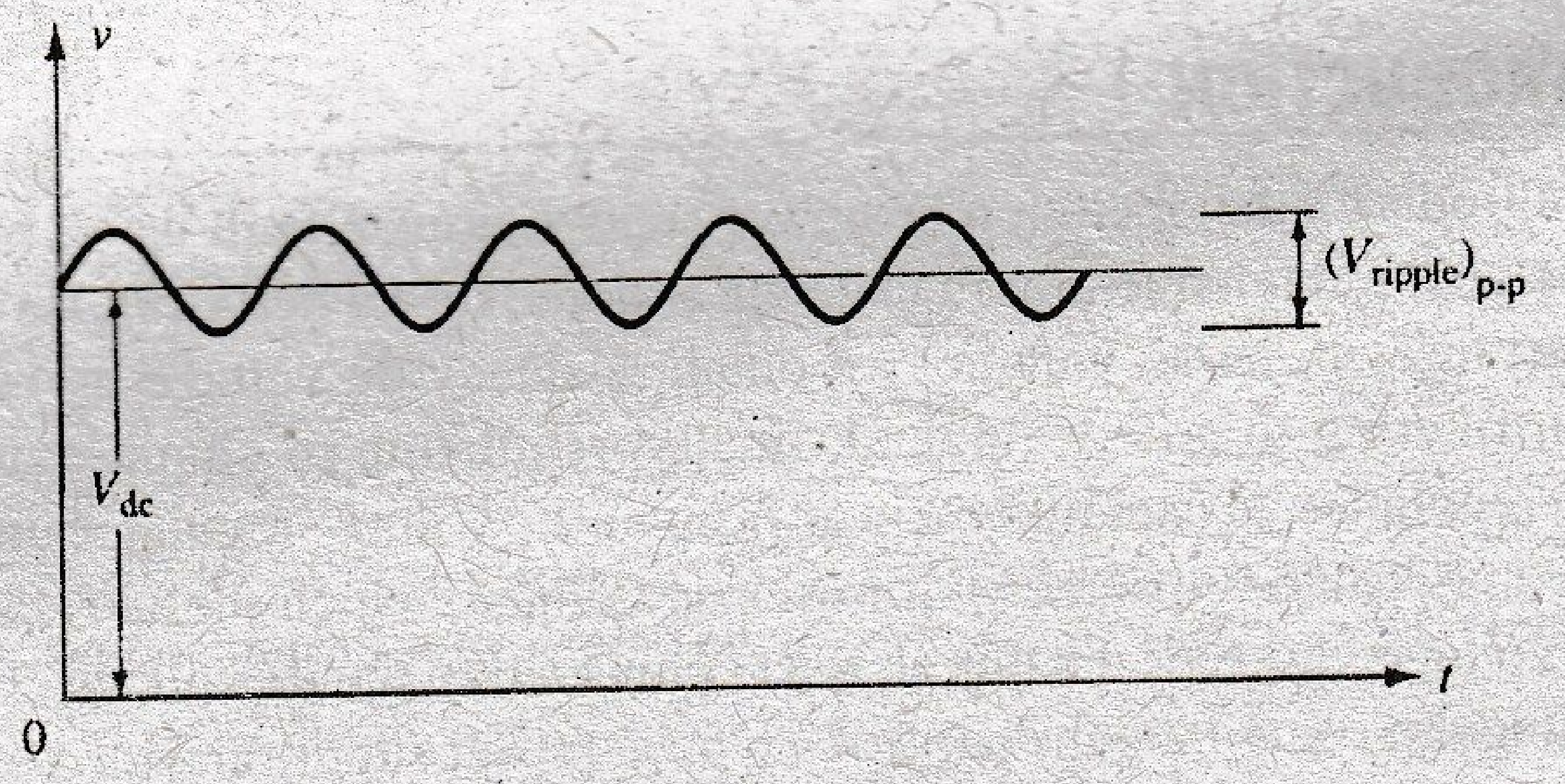


FIG. 15.2
Filter voltage waveform showing dc and ripple voltages.

Consider measuring the output voltage of a filter circuit using a dc voltmeter and an ac (rms) voltmeter. The dc voltmeter will read only the average or dc level of the output voltage. The ac (rms) meter will read only the rms value of the ac component of the output voltage (assuming the ac signal is coupled through a capacitor to block out the dc level).

Definition: Ripple is defined as

$$\boxed{r = \frac{\text{ripple voltage (rms)}}{\text{dc voltage}} = \frac{V_r(\text{rms})}{V_{\text{dc}}} \times 100\%} \tag{15.1}$$

EXAMPLE 15.1 Using a dc and ac voltmeter to measure the output signal from a filter circuit, we obtain readings of 25 V dc and 1.5 V rms. Calculate the ripple of the filter output voltage.

Solution:

$$r = \frac{V_r(\text{rms})}{V_{\text{dc}}} \times 100\% = \frac{1.5\text{ V}}{25\text{ V}} \times 100\% = \mathbf{6\%}$$

Voltage Regulation Another factor of importance in a power supply is the amount the dc output voltage changes over a range of circuit operation. The voltage provided at the output under no-load condition (no current drawn from the supply) is reduced when load current is drawn from the supply (under load). The amount the dc voltage changes between the no-load and load conditions is described by a factor called voltage regulation.

Definition: Voltage regulation is given by

$$\text{Voltage regulation} = \frac{\text{no-load voltage} - \text{full-load voltage}}{\text{full-load voltage}}$$

$$\boxed{\%\text{V.R.} = \frac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}} \times 100\%} \qquad \textbf{(15.2)}$$

EXAMPLE 15.2 A dc voltage supply provides 60 V when the output is unloaded. When connected to a load, the output drops to 56 V. Calculate the value of voltage regulation.

Solution:

$$\text{Eq. (15.2):} \quad \%\text{V.R.} = \frac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}} \times 100\% = \frac{60\text{ V} - 56\text{ V}}{56\text{ V}} \times 100\% = \mathbf{7.1\%}$$

If the value of full-load voltage is the same as the no-load voltage, the voltage regulation calculated is 0%, which is the best expected. This means that the supply is a perfect voltage source for which the output voltage is independent of the current drawn from the supply. The smaller the voltage regulation, the better is the operation of the voltage supply circuit.

Ripple Factor of Rectified Signal Although the rectified voltage is not a filtered voltage, it nevertheless contains a dc component and a ripple component. We will see that the full-wave rectified signal has a larger dc component and less ripple than the half-wave rectified voltage.

Half-wave: For a half-wave rectified signal, the output dc voltage is

$$V_{\text{dc}} = 0.318V_m \qquad \textbf{(15.3)}$$

The rms value of the ac component of the output signal can be calculated (see Appendix C) to be

$$V_r(\text{rms}) = 0.385V_m \qquad \textbf{(15.4)}$$

The percentage ripple of a half-wave rectified signal can then be calculated as

$$r = \frac{V_r(\text{rms})}{V_{\text{dc}}} \times 100\% = \frac{0.385V_m}{0.318V_m} \times 100\% = 121\% \qquad \textbf{(15.5)}$$

Full-wave: For a full-wave rectified voltage the dc value is

$$V_{\text{dc}} = 0.636V_m \qquad \textbf{(15.6)}$$

The rms value of the ac component of the output signal can be calculated (see Appendix C) to be

$$V_r(\text{rms}) = 0.308V_m \qquad \textbf{(15.7)}$$

The percentage ripple of a full-wave rectified signal can then be calculated as

$$r = \frac{V_r(\text{rms})}{V_{\text{dc}}} \times 100\% = \frac{0.308V_m}{0.636V_m} \times 100\% = 48\% \qquad \textbf{(15.8)}$$

In summary, a full-wave rectified signal has less ripple than a half-wave rectified signal and is thus better to apply to a filter.

15.3 CAPACITOR FILTER

A very popular filter circuit is the capacitor-filter circuit shown in Fig. 15.3. A capacitor is connected at the rectifier output, and a dc voltage is obtained across the capacitor. Figure 15.4a shows the output voltage of a full-wave rectifier before the signal is filtered, whereas Fig. 15.4b shows the resulting waveform after the filter capacitor is connected at the rectifier output. Notice that the filtered waveform is essentially a dc voltage with some ripple (or ac variation).

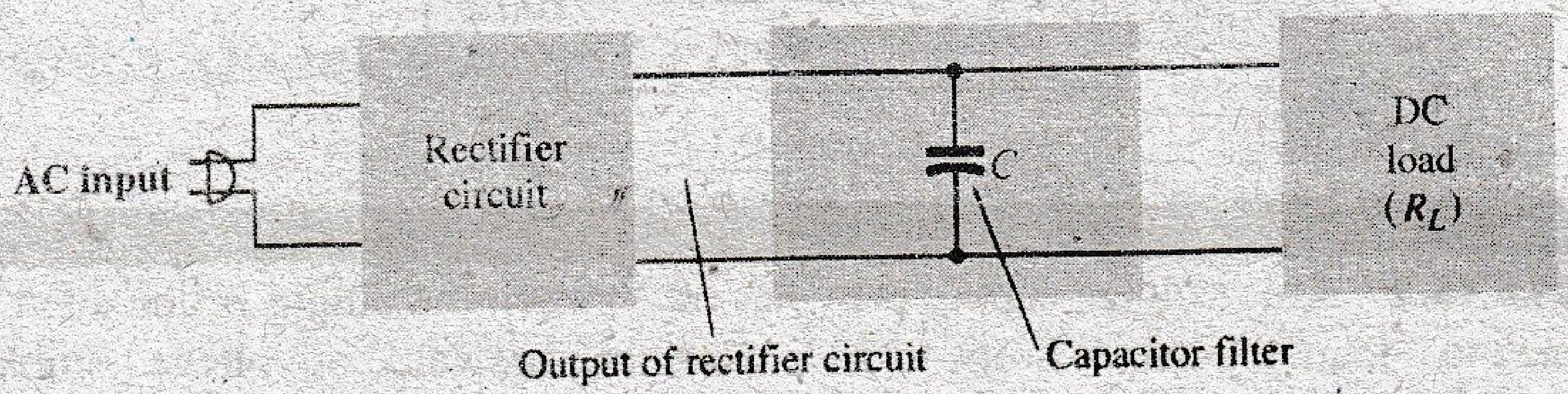


FIG. 15.3
Basic capacitor filter.

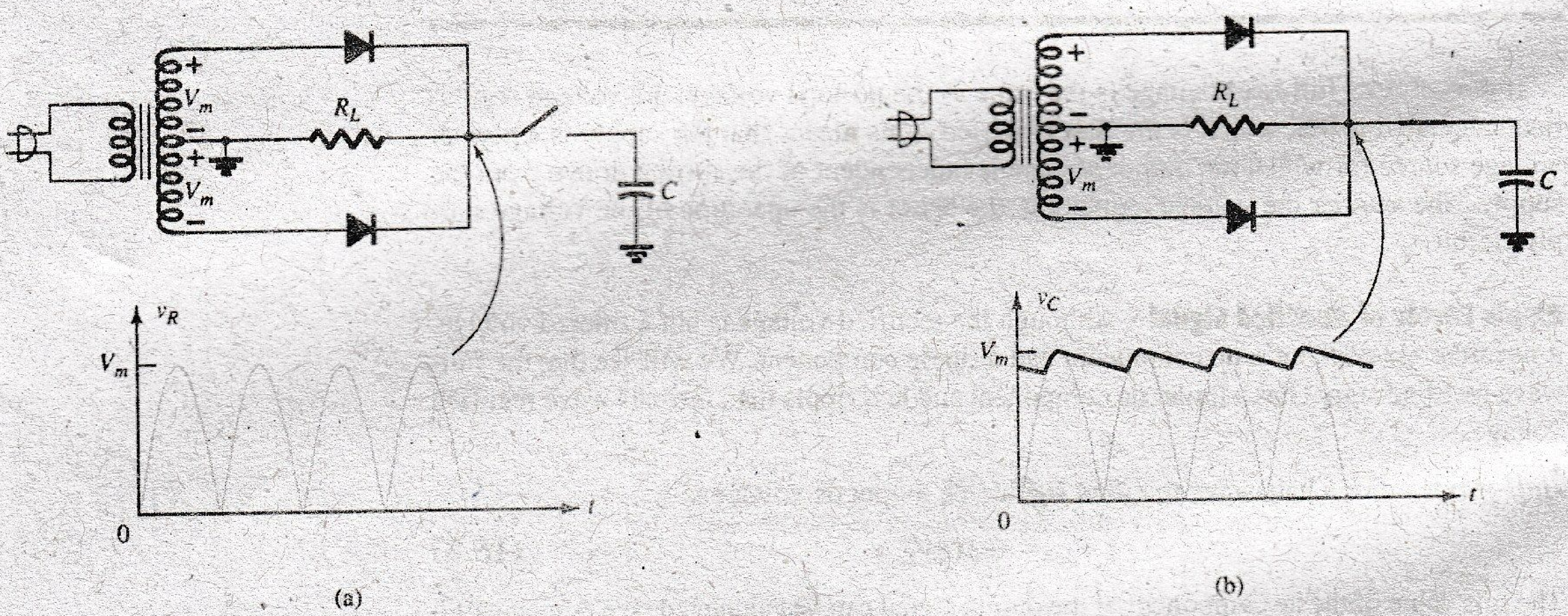


FIG. 15.4
Capacitor filter operation: (a) full-wave rectifier voltage; (b) filtered output voltage.

Figure 15.5a shows a full-wave bridge rectifier and the output waveform obtained from the circuit when connected to a load (R_L). If no load were connected across the capacitor, the output waveform would ideally be a constant dc level equal in value to the peak voltage (V_m) from the rectifier circuit. However, the purpose of obtaining a dc voltage is to provide

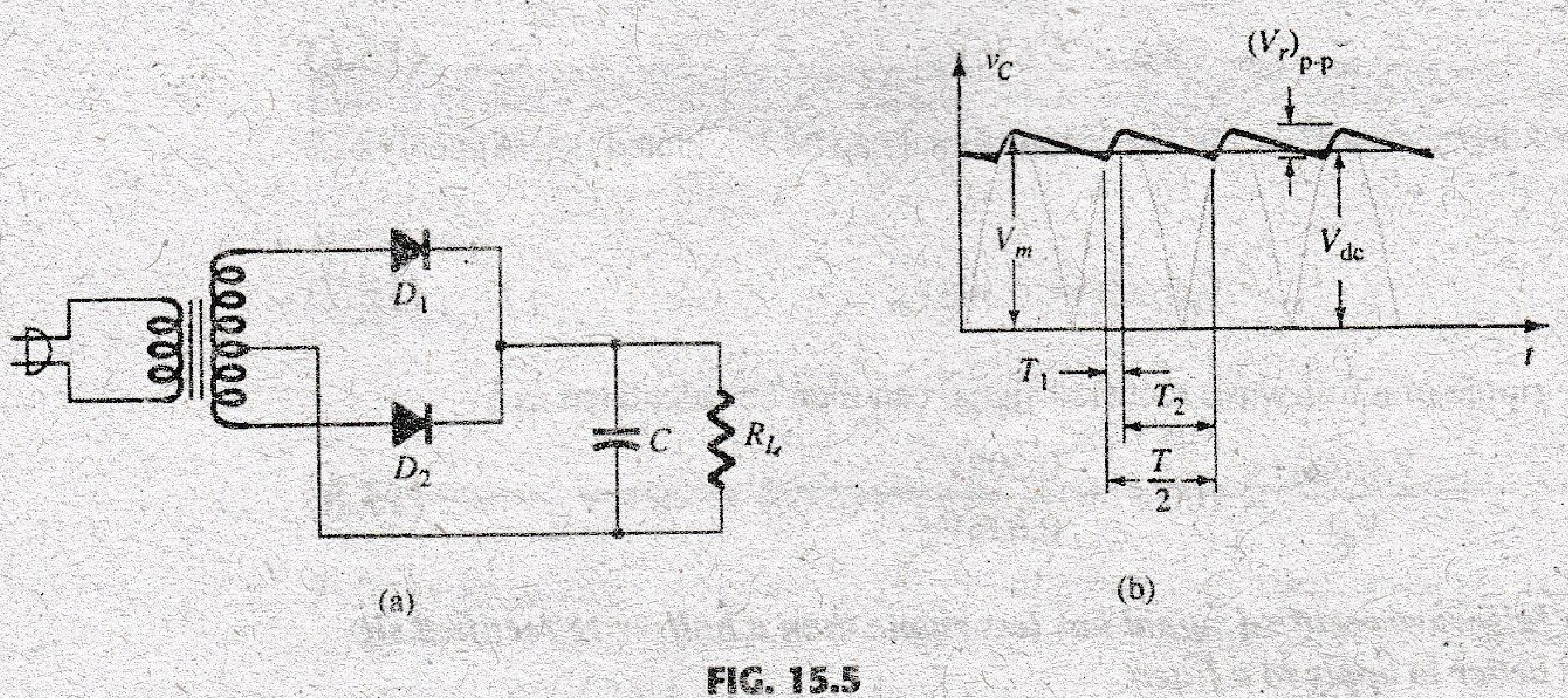


FIG. 15.5
Capacitor filter: (a) capacitor filter circuit; (b) output voltage waveform.

this voltage for use by various electronic circuits, which then constitute a load on the voltage supply. Since there will always be a load on the filter output, we must consider this practical case in our discussion.

Output Waveform

Figure 15.5b shows the waveform across a capacitor filter. Time T_1 is the time during which diodes of the full-wave rectifier conduct, charging the capacitor up to the peak rectifier voltage V_m. Time T_2 is the time interval during which the rectifier voltage drops below the peak voltage, and the capacitor discharges through the load. Since the charge–discharge cycle occurs for each half-cycle for a full-wave rectifier, the period of the rectified waveform is $T/2$. The filtered voltage, as shown in Fig. 15.6, shows the output waveform to have a dc level V_{dc} and a ripple voltage V_r (rms) as the capacitor charges and discharges. Some details of these waveforms and the circuit elements are considered next.

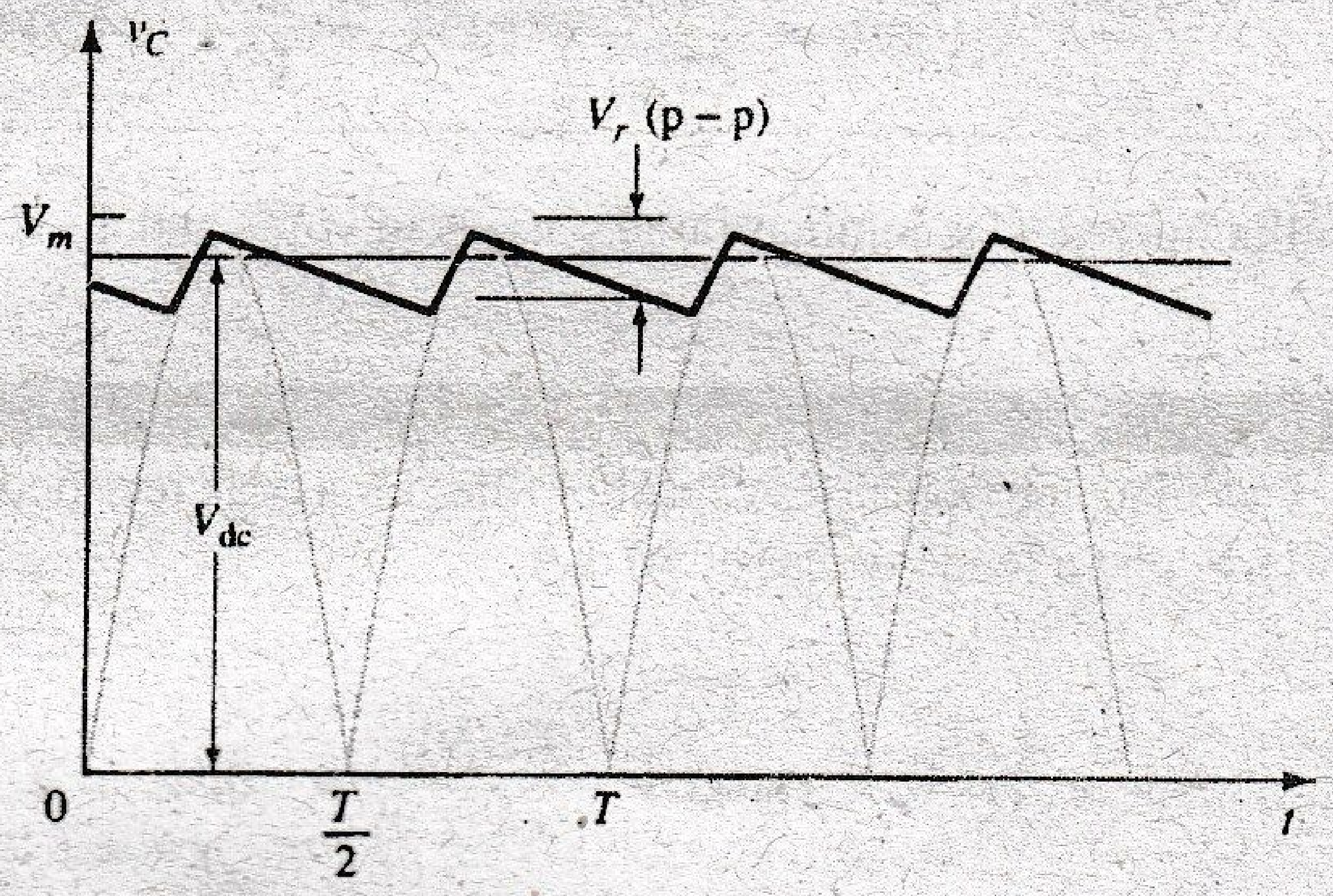


FIG. 15.6
Approximate output voltage of capacitor filter circuit.

Ripple Voltage V_r (RMS) Appendix C provides the details for determining the value of the ripple voltage in terms of the other circuit parameters. The ripple voltage can be calculated from

$$\boxed{V_r(\text{rms}) = \frac{I_{dc}}{4\sqrt{3}fC} = \frac{2.4I_{dc}}{C} = \frac{2.4V_{dc}}{R_LC}} \tag{15.9}$$

where I_{dc} is in milliamperes, C is in microfarads, and R_L is in kilohms.

EXAMPLE 15.3 Calculate the ripple voltage of a full-wave rectifier with a 100-μF filter capacitor connected to a load drawing 50 mA.

Solution:

$$\text{Eq. (15.9):}\quad V_r(\text{rms}) = \frac{2.4(50)}{100} = \mathbf{1.2\ V}$$

DC Voltage V_{dc} From Appendix C, we can express the dc value of the waveform across the filter capacitor as

$$\boxed{V_{dc} = V_m - \frac{I_{dc}}{4fC} = V_m - \frac{4.17I_{dc}}{C}} \tag{15.10}$$

where V_m is the peak rectifier voltage, I_{dc} is the load current in milliamperes, and C is the filter capacitor in microfarads.

EXAMPLE 15.4 If the peak rectified voltage for the filter circuit of Example 15.3 is 30 V, calculate the filter dc voltage.

Solution:

$$\text{Eq. (15.10):}\quad V_{\text{dc}} = V_m - \frac{4.17 I_{\text{dc}}}{C} = 30 - \frac{4.17(50)}{100} = \mathbf{27.9\ V}$$

Filter Capacitor Ripple

Using the definition of ripple [Eq. (15.1)], Eq. (15.9), and Eq. (15.10), with $V_{\text{dc}} \approx V_m$, we can obtain the expression for the output waveform ripple of a full-wave rectifier and filter-capacitor circuit:

$$\boxed{r = \frac{V_r(\text{rms})}{V_{\text{dc}}} \times 100\% = \frac{2.4 I_{\text{dc}}}{C V_{\text{dc}}} \times 100\% = \frac{2.4}{R_L C} \times 100\%} \tag{15.11}$$

where I_{dc} is in milliamperes, C is in microfarads, V_{dc} is in volts, and R_L is in kilohms.

EXAMPLE 15.5 Calculate the ripple of a capacitor filter for a peak rectified voltage of 30 V, capacitor $C = 50\ \mu\text{F}$, and a load current of 50 mA.

Solution:

$$\text{Eq. (15.11):}\quad r = \frac{2.4 I_{\text{dc}}}{C V_{\text{dc}}} \times 100\% = \frac{2.4(50)}{100(27.9)} \times 100\% = \mathbf{4.3\%}$$

We could also calculate the ripple using the basic definition:

$$r = \frac{V_r(\text{rms})}{V_{\text{dc}}} \times 100\% = \frac{1.2\ \text{V}}{27.9\ \text{V}} \times 100\% = \mathbf{4.3\%}$$

Diode Conduction Period and Peak Diode Current

From the previous discussion, it should be clear that larger values of capacitance provide less ripple and higher average voltage, thereby providing better filter action. From this one might conclude that to improve the performance of a capacitor filter it is only necessary to increase the size of the filter capacitor. The capacitor, however, also affects the peak current drawn through the rectifying diodes, and, as will be shown next, the larger the value of the capacitor, the larger is the peak current drawn through the rectifying diodes.

Recall that the diodes conduct during period T_1 (see Fig. 15.5), during which time the diode must provide the necessary average current to charge the capacitor. The shorter this time interval, the larger is the amount of the charging current. Figure 15.7 shows this relation for a half-wave rectified signal (it would be the same basic operation for the full-wave case). Notice that for smaller values of capacitor, with T_1 larger, the peak diode current is less than for larger values of filter capacitor.

Since the average current drawn from the supply must equal the average diode current during the charging period, the following relation can be used (assuming constant diode current during charge time):

$$I_{\text{dc}} = \frac{T_1}{T} I_{\text{peak}}$$

from which we obtain

$$\boxed{I_{\text{peak}} = \frac{T}{T_1} I_{\text{dc}}} \tag{15.12}$$

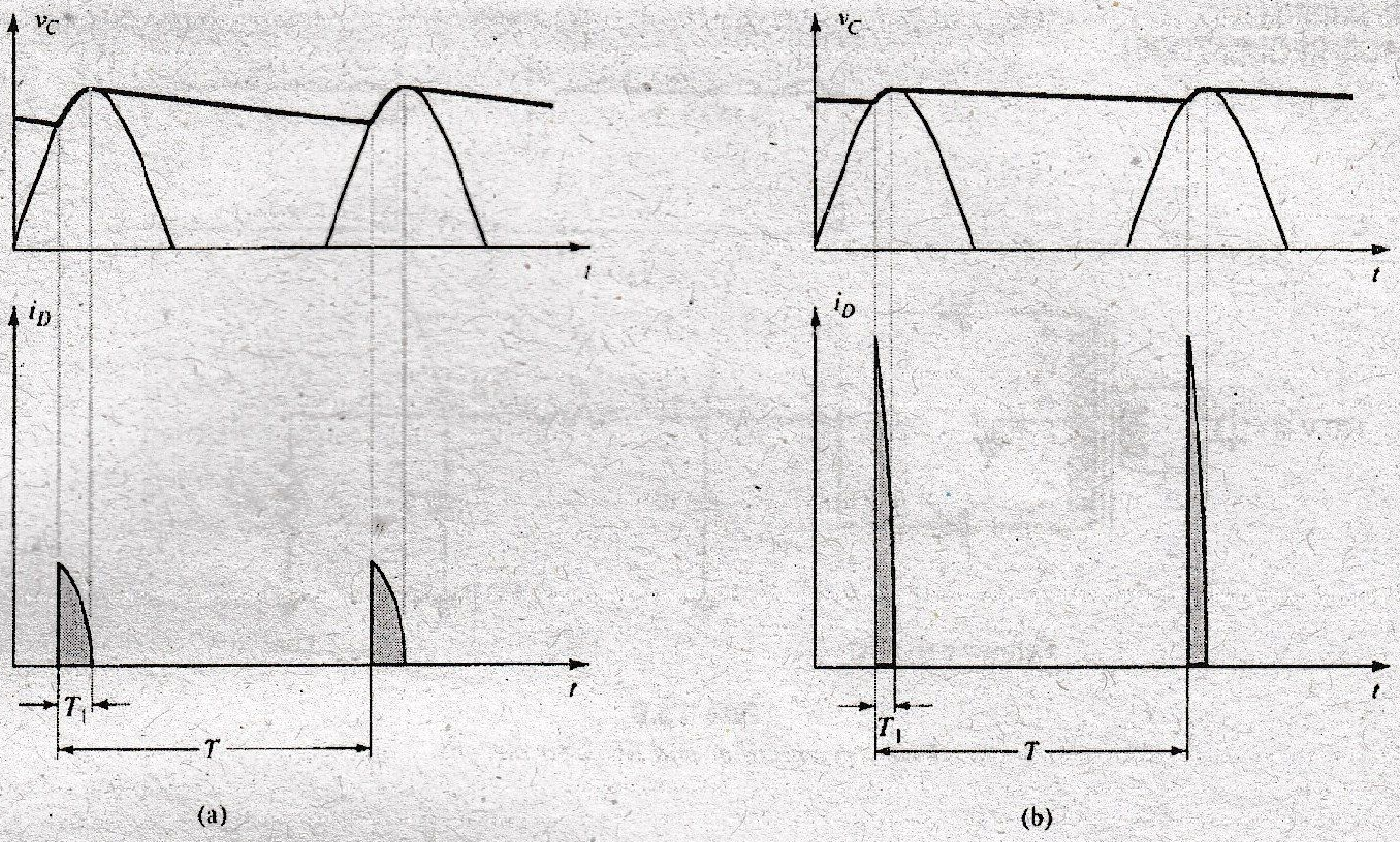


FIG. 15.7
Output voltage and diode current waveforms: (a) small C; (b) large C.

where T_1 = diode conduction time
$T = 1/f$ ($f = 2 \times 60$ for the full-wave case)
I_{dc} = average current drawn from the filter
I_{peak} = peak current through the conducting diodes

15.4 *RC* FILTER

It is possible to further reduce the amount of ripple across a filter capacitor by using an additional *RC* filter section as shown in Fig. 15.8. The purpose of the added *RC* section is to pass most of the dc component while attenuating (reducing) as much of the ac component as possible. Figure 15.9 shows a full-wave rectifier with capacitor filter followed by an *RC* filter section. The operation of the filter circuit can be analyzed using superposition for the dc and ac components of the signal.

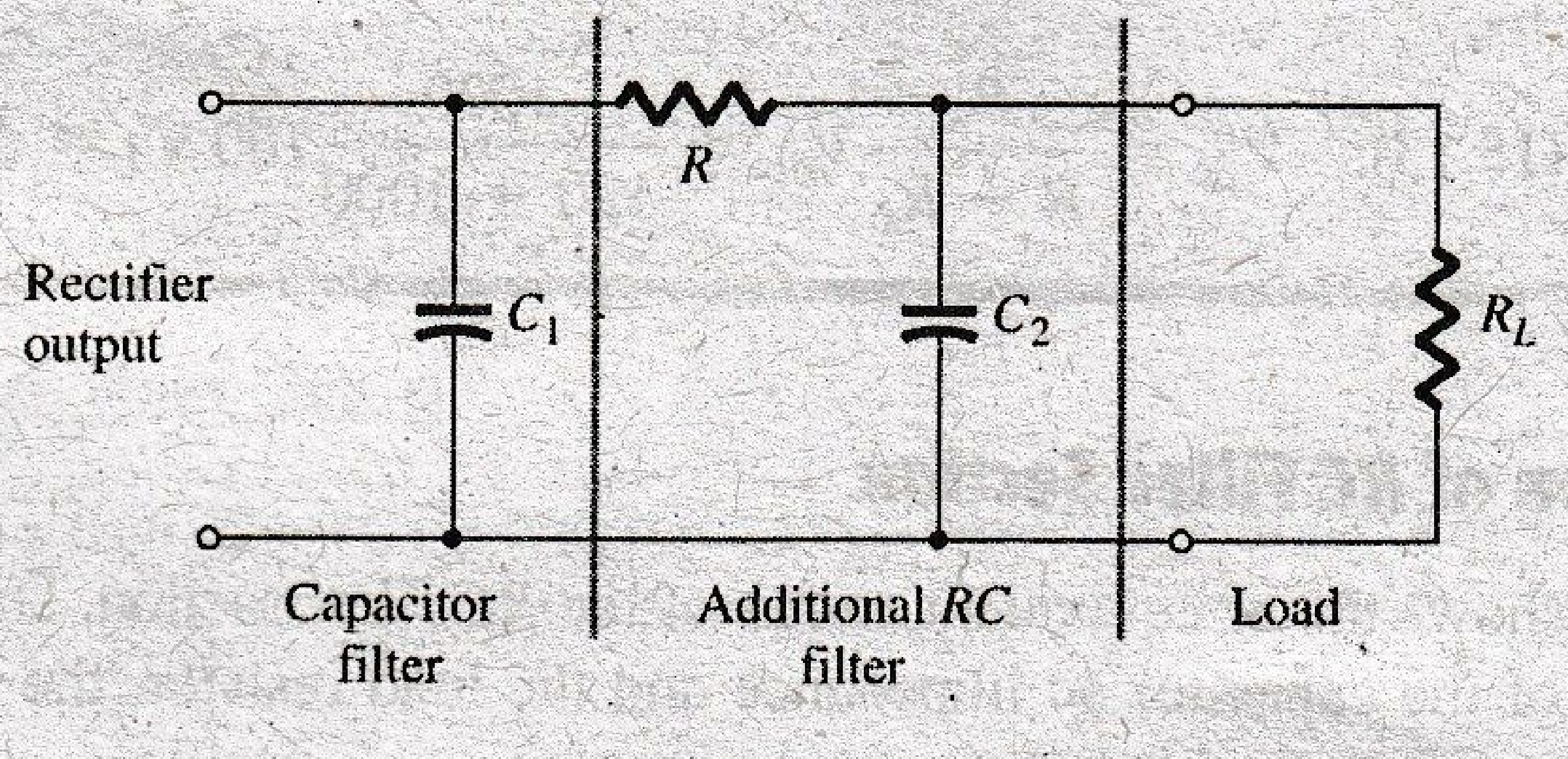


FIG. 15.8
RC filter stage.

DC Operation of *RC* Filter Section

Figure 15.10a shows the dc equivalent circuit to use in analyzing the *RC* filter circuit of Fig. 15.9. Since both capacitors are open-circuit for dc operation, the resulting output dc voltage is

$$\boxed{V'_{dc} = \frac{R_L}{R + R_L} V_{dc}} \qquad (15.13)$$

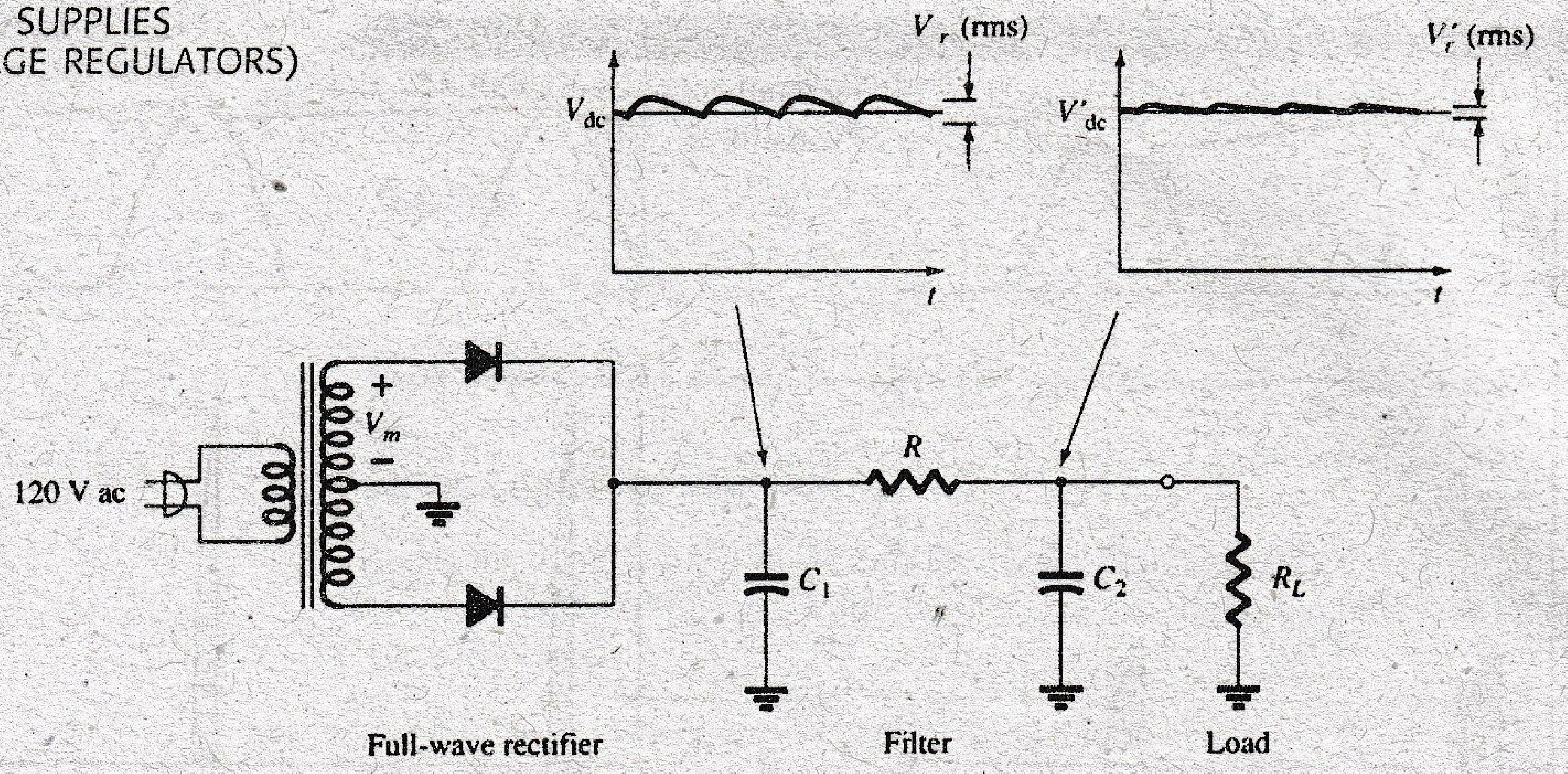


FIG. 15.9
Full-wave rectifier and RC filter circuit.

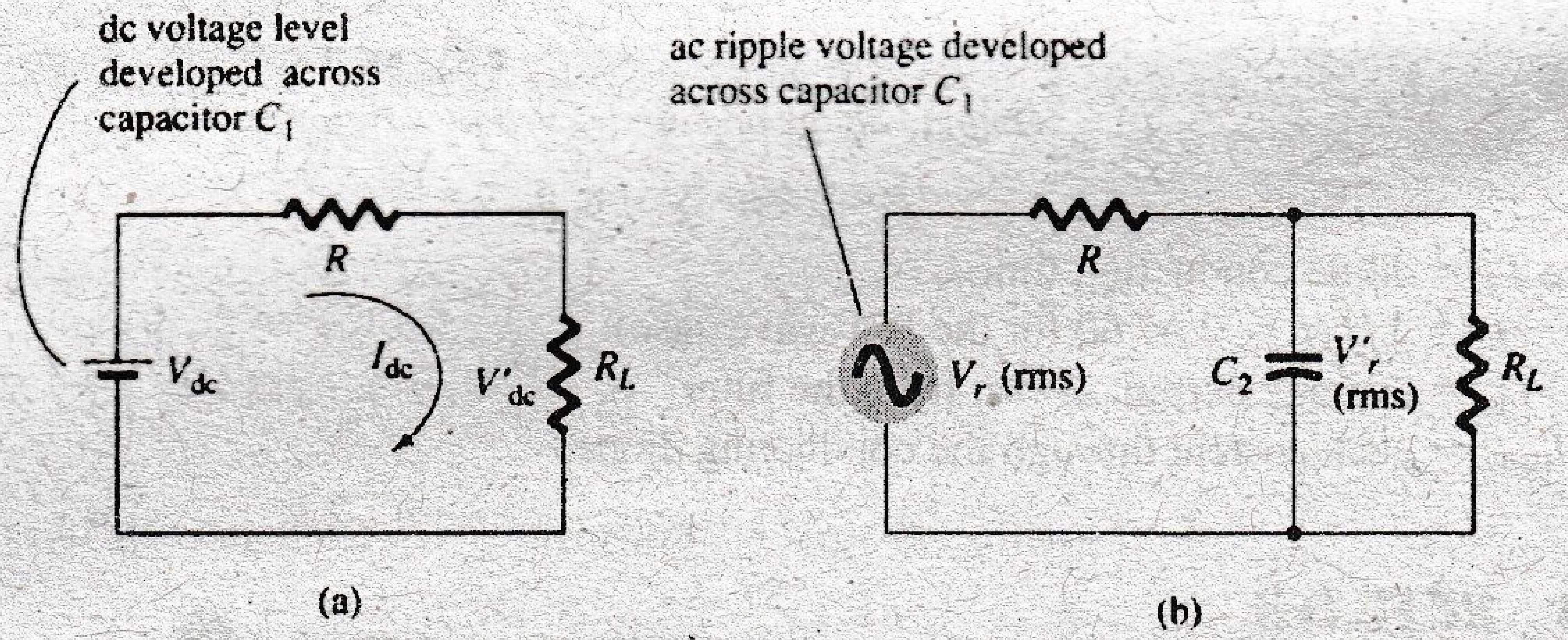


FIG. 15.10
(a) DC and (b) ac equivalent circuits of RC filter.

EXAMPLE 15.6 Calculate the dc voltage across a 1-kΩ load for an RC filter section ($R = 120\ \Omega$, $C = 10\ \mu\text{F}$). The dc voltage across the initial filter capacitor is $V_{dc} = 60$ V.

Solution:

$$\text{Eq. (15.13):}\quad V'_{dc} = \frac{R_L}{R + R_L} V_{dc} = \frac{1000}{120 + 1000}(60\text{ V}) = \mathbf{53.6\ V}$$

AC Operation of *RC* Filter Section

Figure 15.10b shows the ac equivalent circuit of the RC filter section. Due to the voltage-divider action of the capacitor ac impedance and the load resistor, the ac component of voltage resulting across the load is

$$\boxed{V'_r(\text{rms}) \approx \frac{X_C}{R} V_r(\text{rms})} \qquad \textbf{(15.14)}$$

For a full-wave rectifier with ac ripple at 120 Hz, the impedance of a capacitor can be calculated using

$$\boxed{X_C = \frac{1.3}{C}} \qquad \textbf{(15.15)}$$

where C is in microfarads and X_C is in kilohms.

EXAMPLE 15.7 Calculate the dc and ac components of the output signal across load R_L in the circuit of Fig. 15.11. Calculate the ripple of the output waveform.

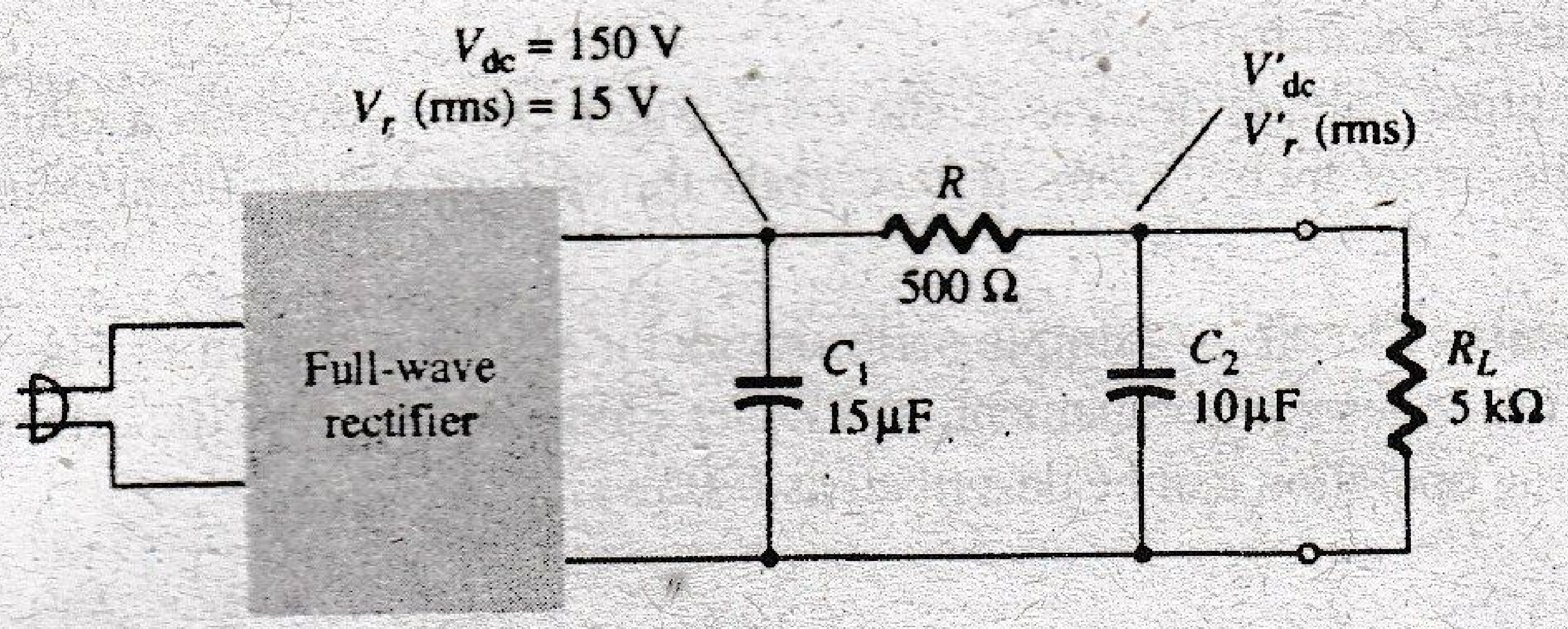


FIG. 15.11
RC filter circuit for Example 15.7.

Solution:

DC Calculation We obtain

$$\text{Eq. (15.13):}\quad V'_{dc} = \frac{R_L}{R + R_L}V_{dc} = \frac{5\text{ k}\Omega}{500 + 5\text{ k}\Omega}(150\text{ V}) = \mathbf{136.4\text{ V}}$$

AC Calculation The *RC*-section capacitive impedance is

$$\text{Eq. (15.15):}\quad X_C = \frac{1.3}{C} = \frac{1.3}{10} = 0.13\text{ k}\Omega = 130\ \Omega$$

The ac component of the output voltage, calculated using Eq. (15.14), is

$$V'_r(\text{rms}) = \frac{X_C}{R}V_r(\text{rms}) = \frac{130}{500}(15\text{ V}) = \mathbf{3.9\text{ V}}$$

The ripple of the output waveform is then

$$r = \frac{V'_r(\text{rms})}{V'_{dc}} \times 100\% = \frac{3.9\text{ V}}{136.4\text{ V}} \times 100\% = \mathbf{2.86\%}$$

15.5 DISCRETE TRANSISTOR VOLTAGE REGULATION

Two types of transistor voltage regulators are the series voltage regulator and the shunt voltage regulator. Each type of circuit can provide an output dc voltage that is regulated or maintained at a set value even if the input voltage varies or if the load connected to the output changes.

Series Voltage Regulation

The basic connection of a series regulator circuit is shown in the block diagram of Fig. 15.12. The series element controls the amount of the input voltage that gets to the output.

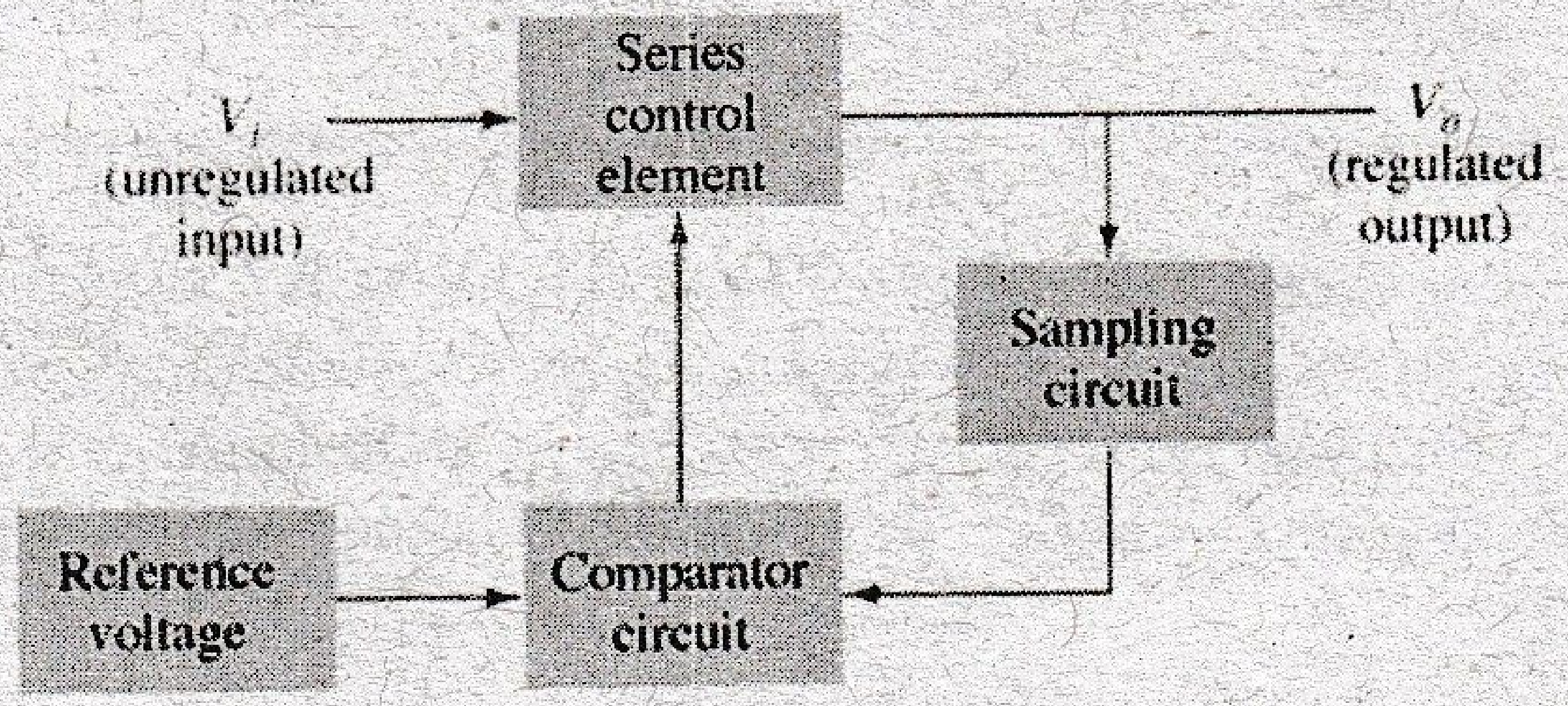


FIG. 15.12
Series regulator block diagram.

The output voltage is sampled by a circuit that provides a feedback voltage to be compared to a reference voltage.

1. If the output voltage increases, the comparator circuit provides a control signal to cause the series control element to decrease the amount of the output voltage—thereby maintaining the output voltage.
2. If the output voltage decreases, the comparator circuit provides a control signal to cause the series control element to increase the amount of the output voltage.

Series Regulator Circuit A simple series regulator circuit is shown in Fig. 15.13. Transistor Q_1 is the series control element, and Zener diode D_Z provides the reference voltage. The regulating operation can be described as follows:

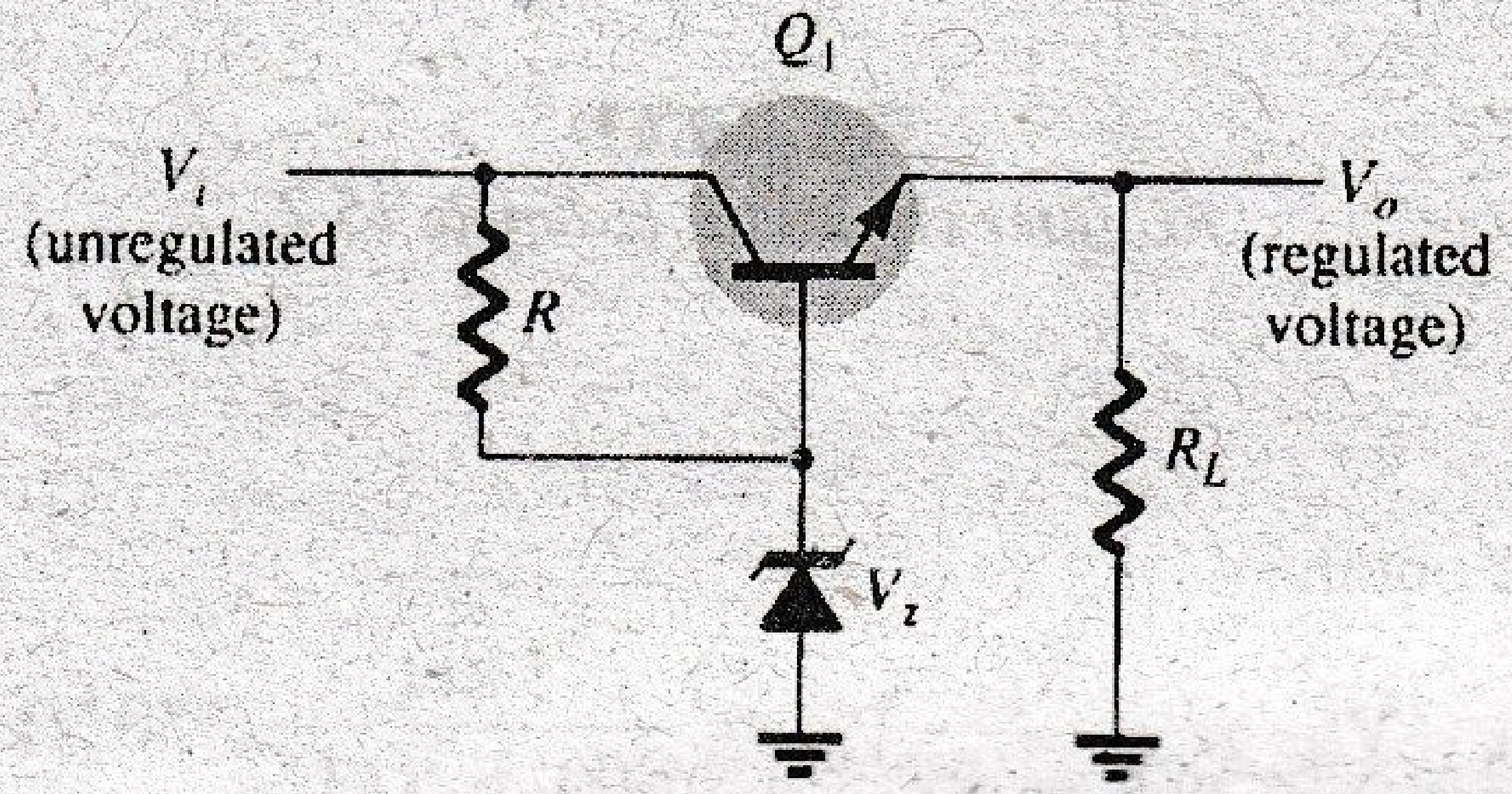


FIG. 15.13
Series regulator circuit.

1. If the output voltage decreases, the increased base-emitter voltage causes transistor Q_1 to conduct more, thereby raising the output voltage—maintaining the output constant.
2. If the output voltage increases, the decreased base-emitter voltage causes transistor Q_1 to conduct less, thereby reducing the output voltage—maintaining the output constant.

EXAMPLE 15.8 Calculate the output voltage and the Zener current in the regulator circuit of Fig. 15.14 for $R_L = 1\text{ k}\Omega$.

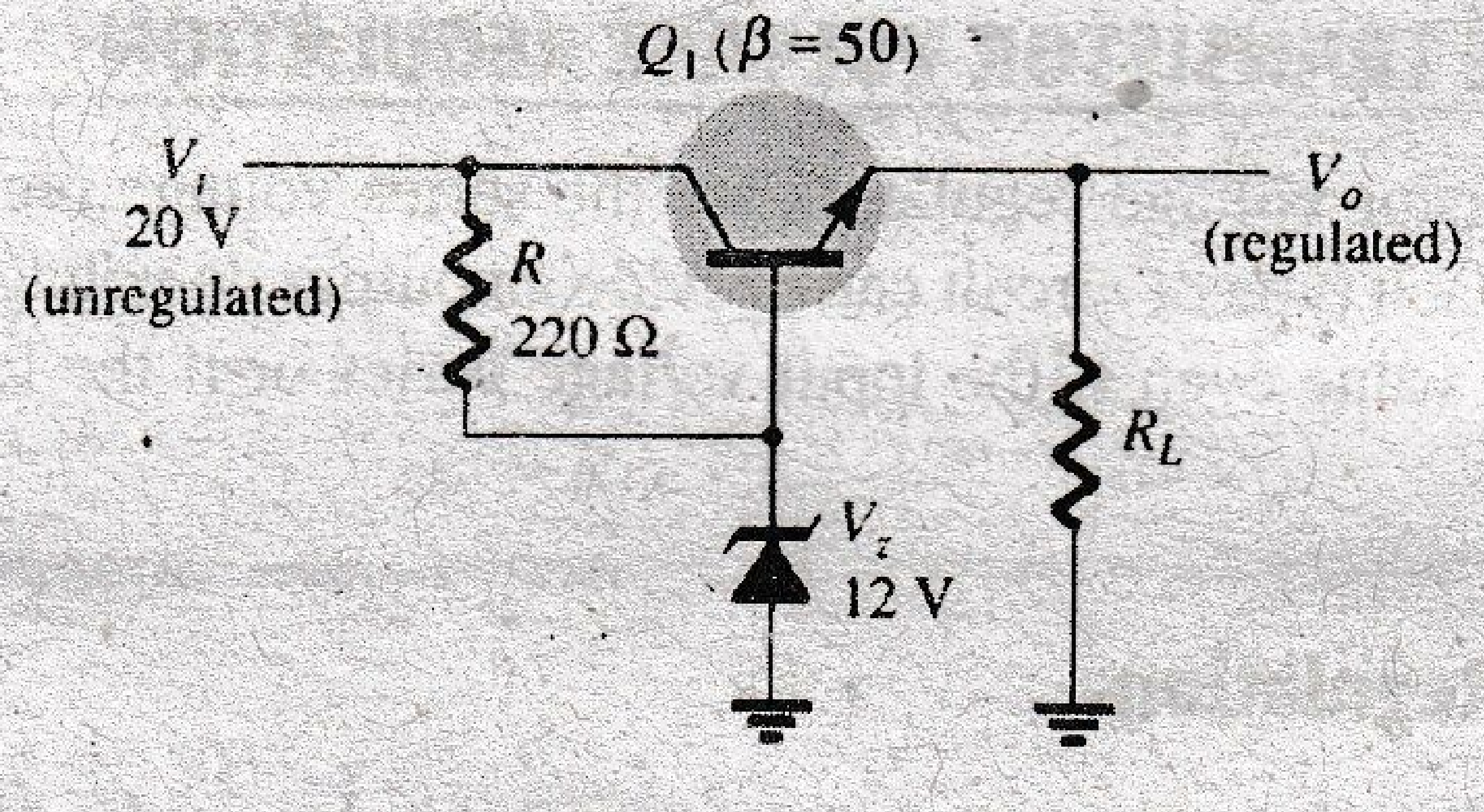


FIG. 15.14
Circuit for Example 15.8.

Solution:

$$V_o = V_Z - V_{BE} = 12\text{ V} - 0.7\text{ V} = \mathbf{11.3\text{ V}}$$
$$V_{CE} = V_i - V_o = 20\text{ V} - 11.3\text{ V} = 8.7\text{ V}$$
$$I_R = \frac{20\text{ V} - 12\text{ V}}{220\ \Omega} = \frac{8\text{ V}}{220\ \Omega} = 36.4\text{ mA}$$

For $R_L = 1\text{ k}\Omega$,

$$I_L = \frac{V_o}{R_L} = \frac{11.3\text{ V}}{1\text{ k}\Omega} = 11.3\text{ mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{11.3\text{ mA}}{50} = 226\ \mu\text{A}$$

$$I_Z = I_R - I_B = 36.4\text{ mA} - 226\ \mu\text{A} \approx \mathbf{36\ mA}$$

Improved Series Regulator An improved series regulator circuit is shown in Fig. 15.15. Resistors R_1 and R_2 act as a sampling circuit, with Zener diode D_Z providing a reference voltage, and transistor Q_2 then controls the base current to transistor Q_1 to vary the current passed by transistor Q_1 to maintain the output voltage constant.

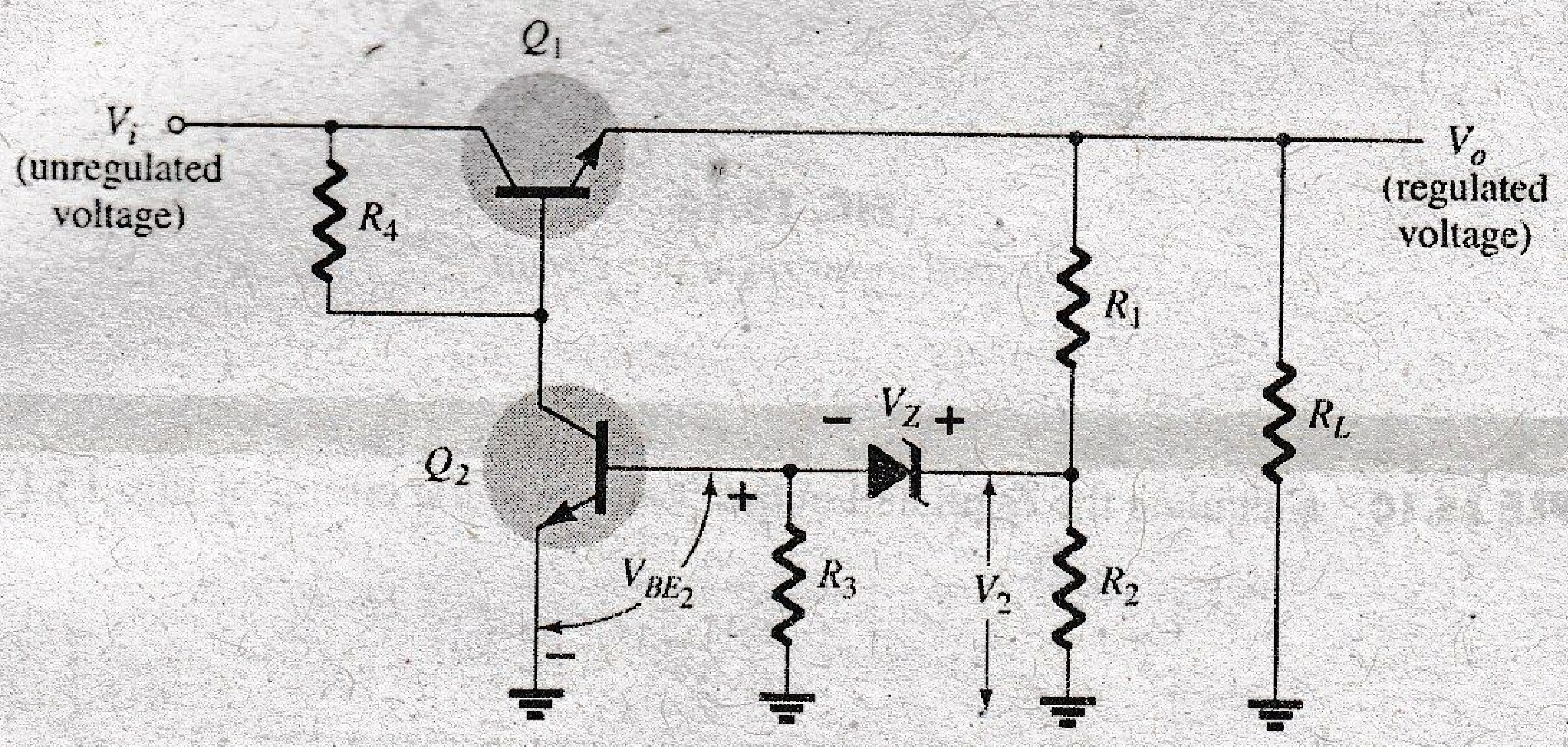


FIG. 15.15
Improved series regulator circuit.

If the output voltage tries to increase, the increased voltage, V_2, sampled by R_1 and R_2, causes the base-emitter voltage of transistor Q_2 to go up (since V_Z remains fixed). If Q_2 conducts more current, less goes to the base of transistor Q_1, which then passes less current to the load, reducing the output voltage—thereby maintaining the output voltage constant. The opposite takes place if the output voltage tries to decrease, causing less current to be supplied to the load, to keep the voltage from decreasing.

The voltage V_2 provided by sensing resistors R_1 and R_2 must equal the sum of the base-emitter voltage of Q_2 and the Zener diode, that is,

$$V_{BE_2} + V_Z = V_2 = \frac{R_2}{R_1 + R_2} V_o \qquad \textbf{(15.16)}$$

Solving Eq. (15.16) for the regulated output voltage V_o gives

$$\boxed{V_o = \frac{R_1 + R_2}{R_2}(V_Z + V_{BE_2})} \qquad \textbf{(15.17)}$$

EXAMPLE 15.9 What regulated output voltage is provided by the circuit of Fig. 15.15 for the circuit elements $R_1 = 20\text{ k}\Omega$, $R_2 = 30\text{ k}\Omega$, and $V_Z = 8.3\text{ V}$?

Solution: From Eq. (15.17), the regulated output voltage is

$$V_o = \frac{20\text{ k}\Omega + 30\text{ k}\Omega}{30\text{ k}\Omega}(8.3\text{ V} + 0.7\text{ V}) = \mathbf{15\ V}$$

Op-Amp Series Regulator Another type of series regulator is shown in Fig. 15.16. The op-amp compares the Zener diode reference voltage with the feedback voltage from sensing resistors R_1 and R_2. If the output voltage varies, the conduction of transistor Q_1 is controlled to maintain the output voltage constant. The output voltage will be maintained at a value of

$$\boxed{V_o = \left(1 + \frac{R_1}{R_2}\right)V_Z} \qquad \textbf{(15.18)}$$

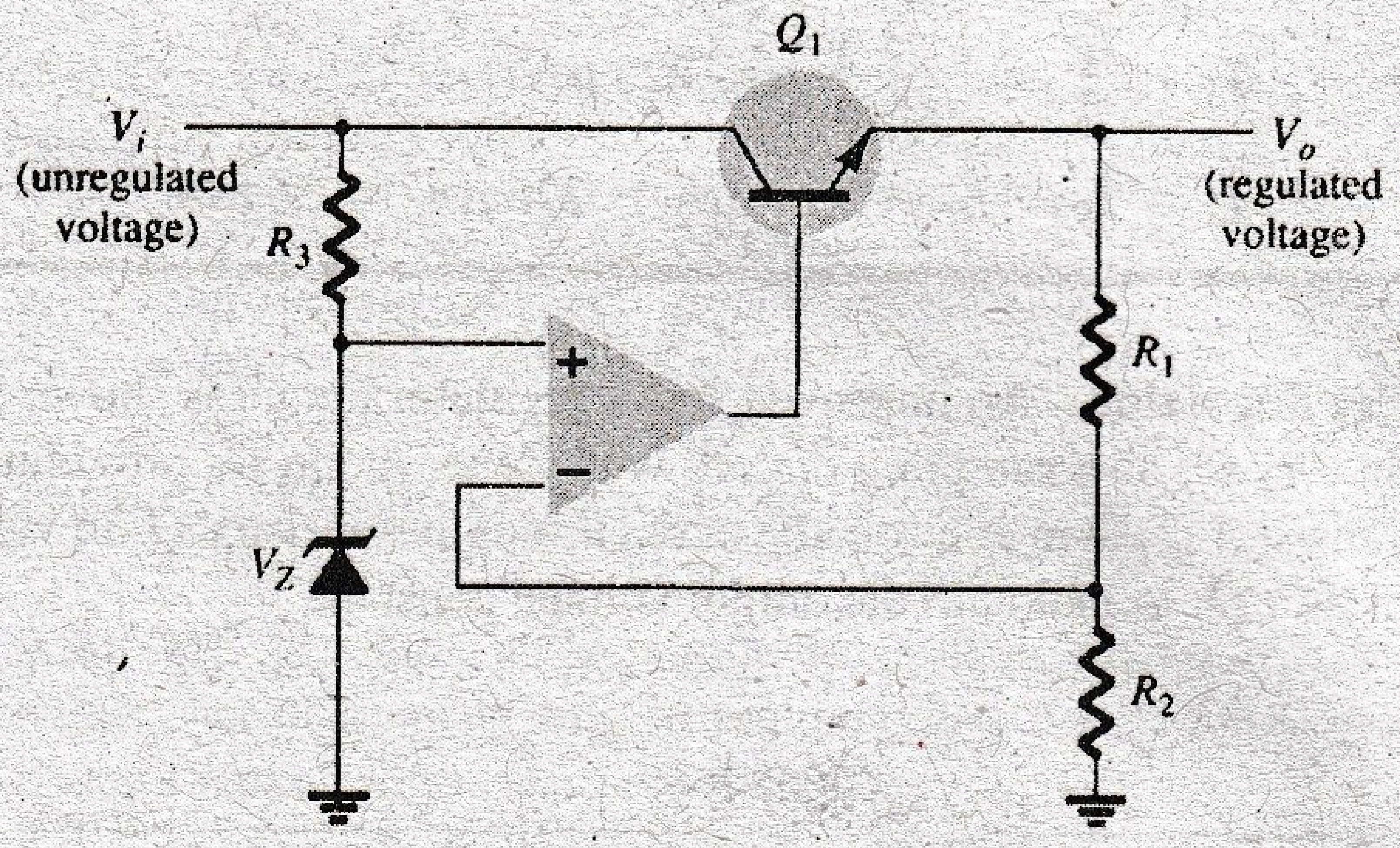


FIG. 15.16
Op-amp series regulator circuit.

EXAMPLE 15.10 Calculate the regulated output voltage in the circuit of Fig. 15.17.

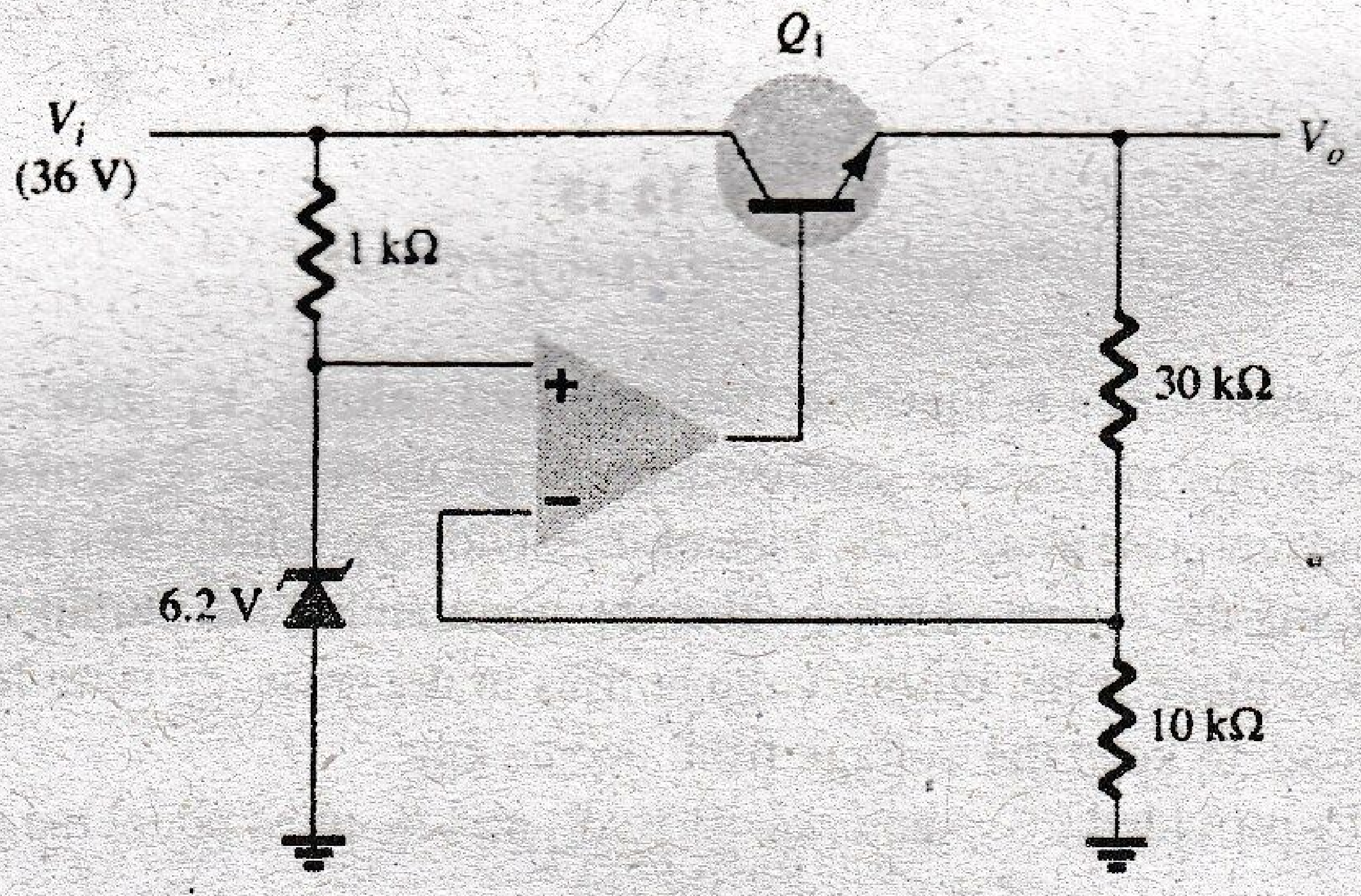


FIG. 15.17
Circuit for Example 15.10.

Solution:

$$\text{Eq. (15.18):}\quad V_o = \left(1 + \frac{30\text{ k}\Omega}{10\text{ k}\Omega}\right)6.2\text{ V} = \mathbf{24.8\text{ V}}$$

Current-Limiting Circuit One form of short-circuit or overload protection is current limiting, as shown in Fig. 15.18. As load current I_L increases, the voltage drop across the short-circuit sensing resistor R_{SC} increases. When the voltage drop across R_{SC} becomes large enough, it will drive Q_2 on, diverting current from the base of transistor Q_1, thereby reducing the load current through transistor Q_1, preventing any additional current to load R_L. The action of components R_{SC} and Q_2 limits the maximum load current.

Foldback Limiting Current limiting reduces the load voltage when the current becomes larger than the limiting value. The circuit of Fig. 15.19 provides foldback limiting, which reduces both the output voltage and the output current, protecting the load from overcurrent as well as protecting the regulator.

Foldback limiting is provided by the additional voltage-divider network of R_4 and R_5 in the circuit of Fig. 15.19 (over that of Fig. 15.17). The divider circuit senses the voltage at the output (emitter) of Q_1. When I_L increases to its maximum value, the voltage across R_{SC} becomes large enough to drive Q_2 on, thereby providing current limiting. If the load resistance is made smaller, the voltage driving Q_2 on becomes less, so that I_L drops when V_L also

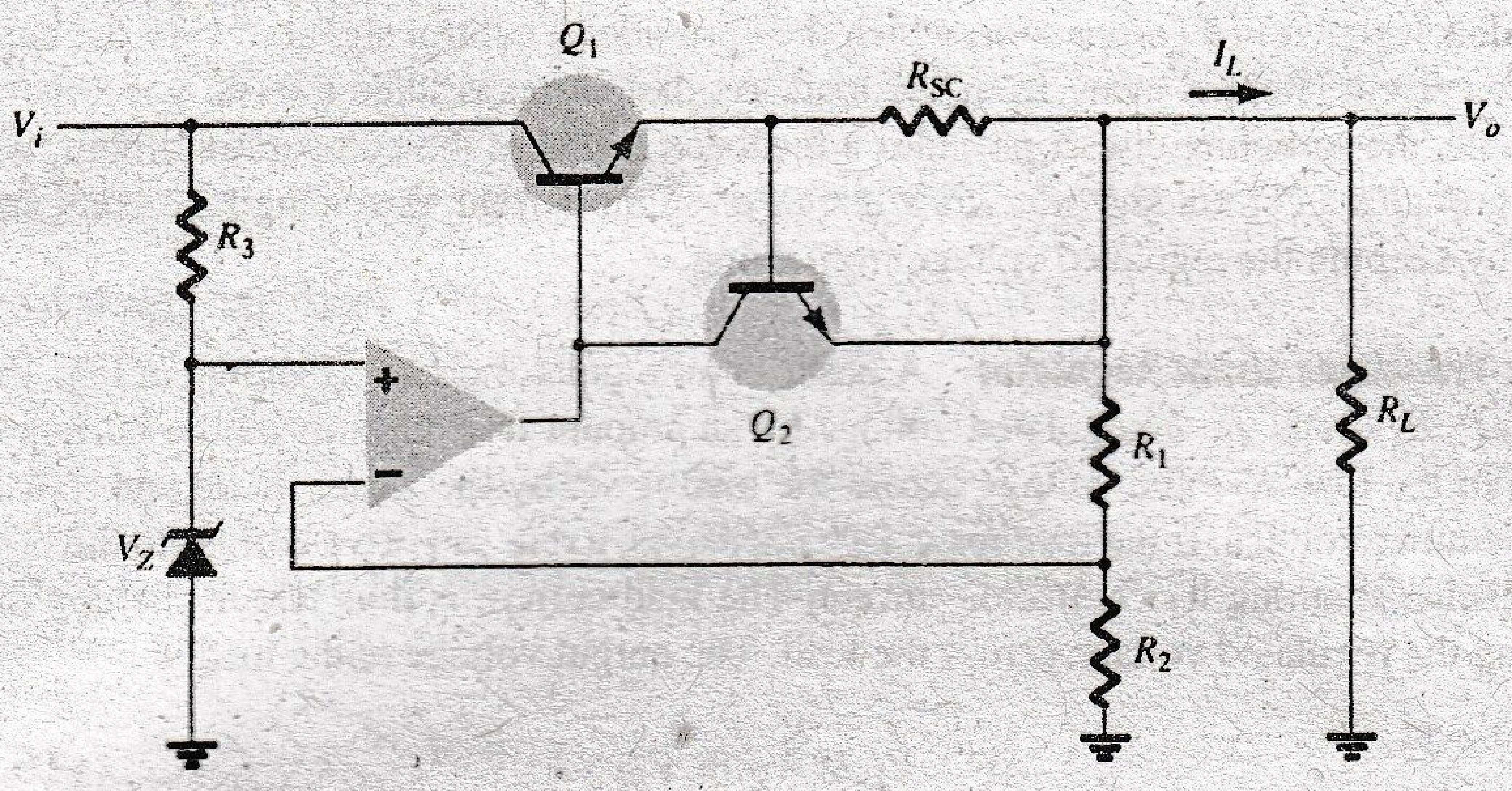


FIG. 15.18
Current-limiting voltage regulator.

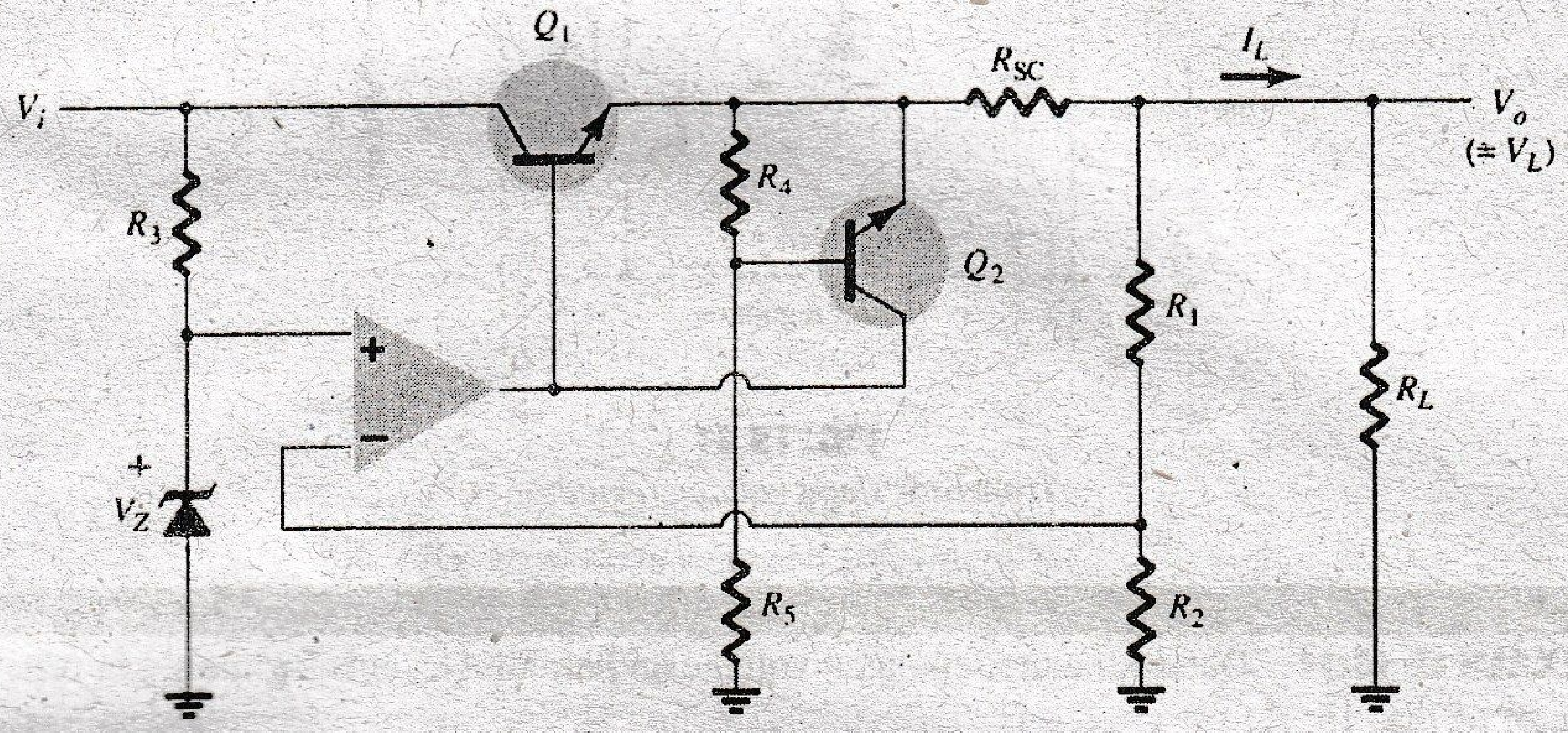


FIG. 15.19
Foldback-limiting series regulator circuit.

drops in value—this action being foldback limiting. When the load resistance is returned to its rated value, the circuit resumes its voltage regulation action.

Shunt Voltage Regulation

A shunt voltage regulator provides regulation by shunting current away from the load to regulate the output voltage. Figure 15.20 shows the block diagram of such a voltage regulator. The input unregulated voltage provides current to the load. Some of the current is pulled away by the control element to maintain the regulated output voltage across the load. If the load voltage tries to change due to a change in the load, the sampling circuit provides

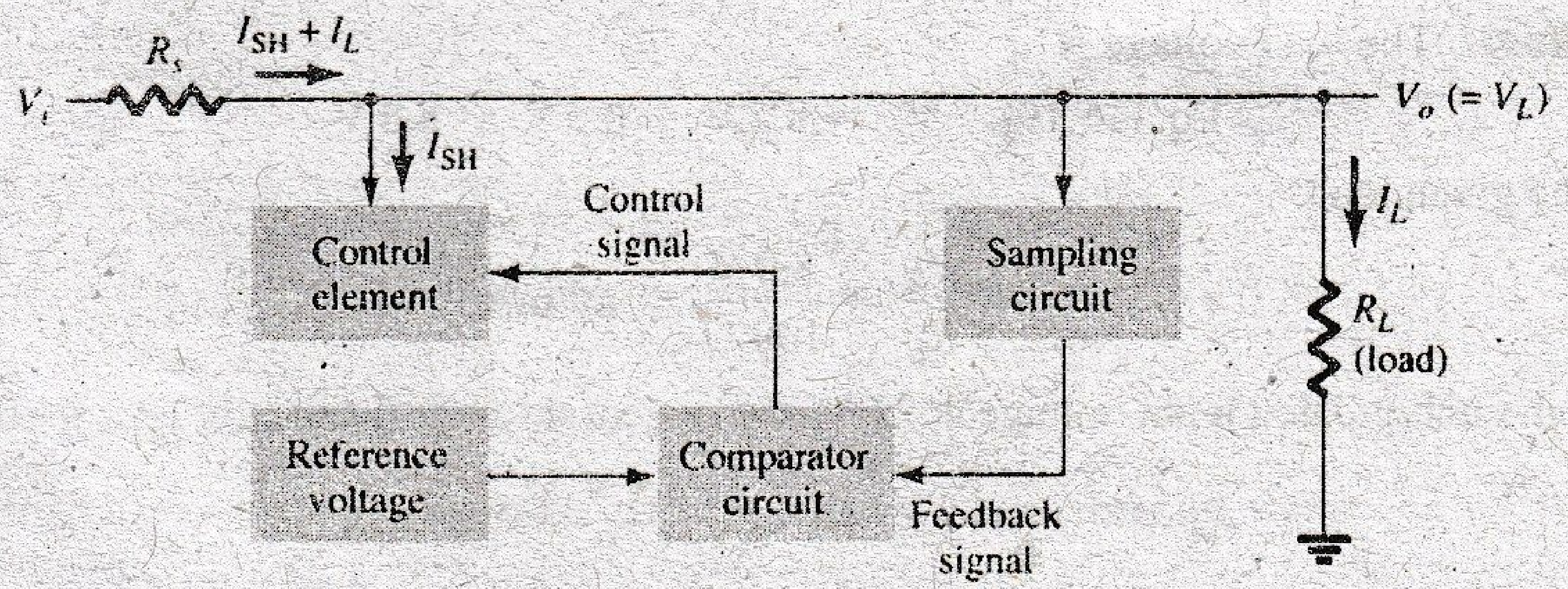


FIG. 15.20
Block diagram of shunt voltage regulator.

a feedback signal to a comparator, which then provides a control signal to vary the amount of the current shunted away from the load. As the output voltage tries to get larger, for example, the sampling circuit provides a feedback signal to the comparator circuit, which then provides a control signal to draw increased shunt current, providing less load current, thereby keeping the regulated voltage from rising.

Basic Transistor Shunt Regulator A basic shunt regulator circuit is shown in Fig. 15.21. Resistor R_S drops the unregulated voltage by an amount that depends on the current supplied to the load R_L. The voltage across the load is set by the Zener diode and transistor base-emitter voltage. If the load resistance decreases, a reduced drive current to the base of Q_1 results, shunting less collector current. The load current is thus larger, thereby maintaining the regulated voltage across the load. The output voltage to the load is

$$V_L = V_Z + V_{BE} \tag{15.19}$$

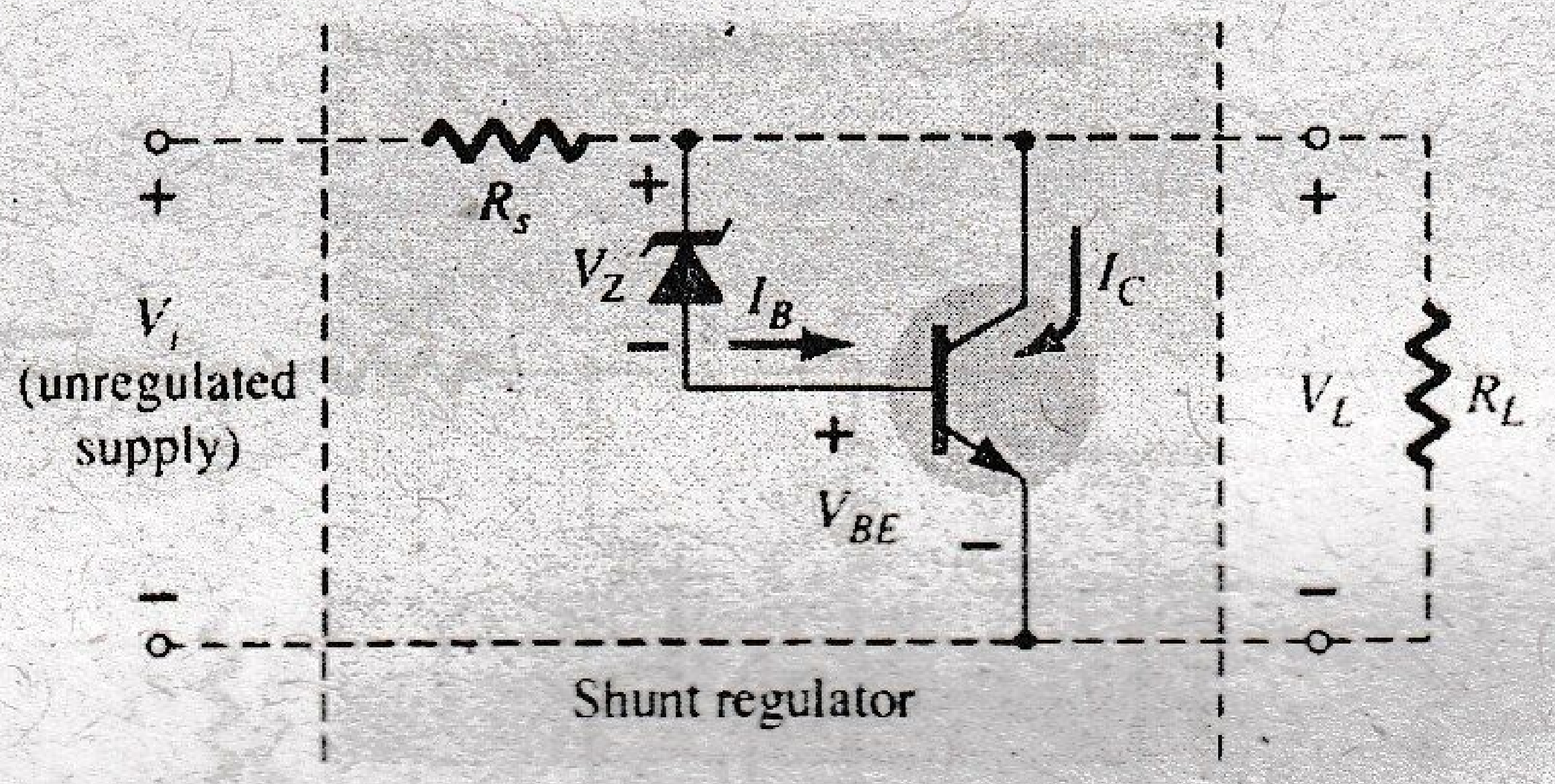


FIG. 15.21
Transistor shunt voltage regulator.

EXAMPLE 15.11 Determine the regulated voltage and circuit currents for the shunt regulator of Fig. 15.22.

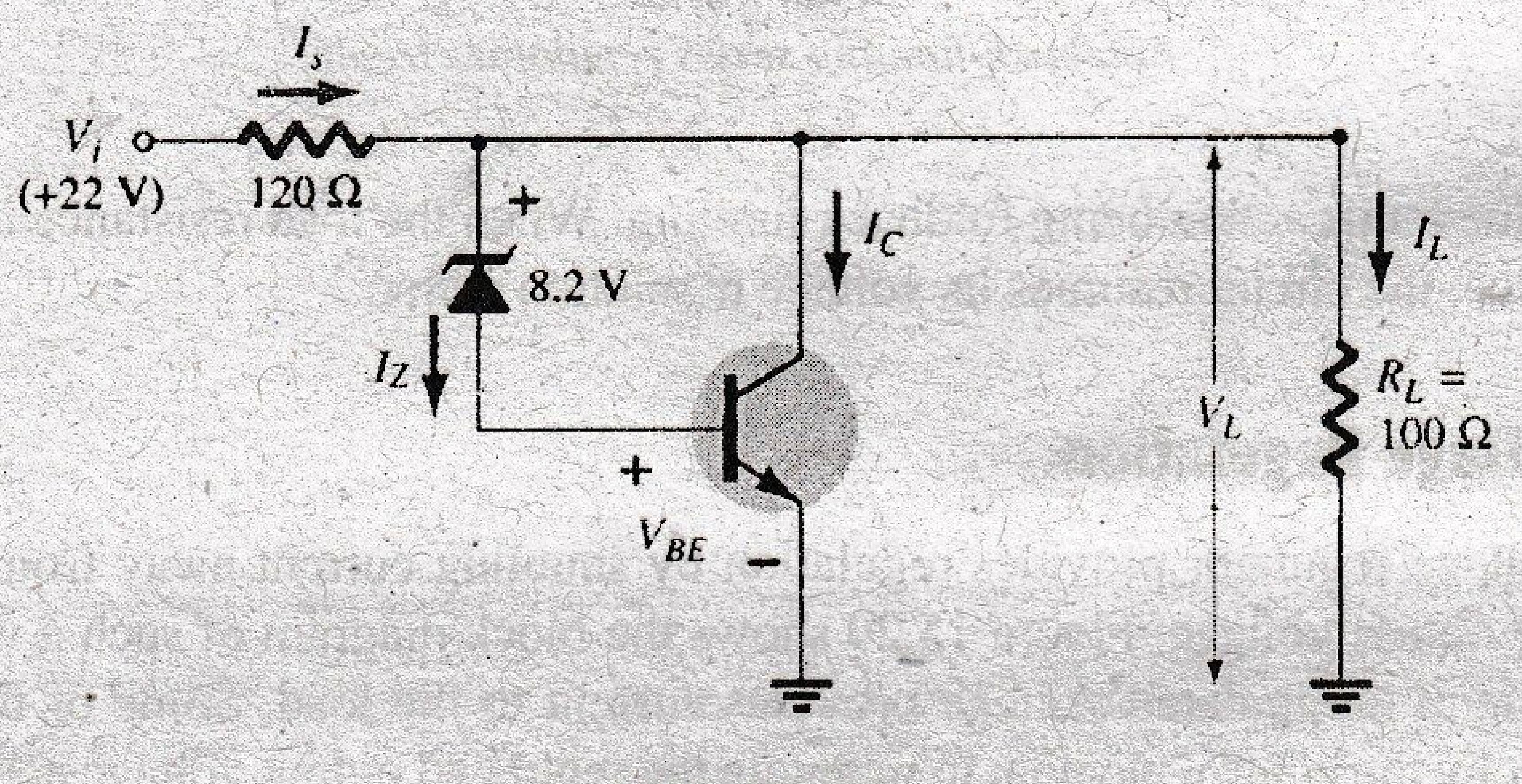


FIG. 15.22
Circuit for Example 15.11.

Solution: The load voltage is

$$\text{Eq. (15.19):} \quad V_L = 8.2\text{ V} + 0.7\text{ V} = \mathbf{8.9\ V}$$

For the given load,

$$I_L = \frac{V_L}{R_L} = \frac{8.9\text{ V}}{100\ \Omega} = \mathbf{89\ mA}$$

With the unregulated input voltage at 22 V, the current through R_S is

$$I_S = \frac{V_i - V_L}{R_S} = \frac{22\text{ V} - 8.9\text{ V}}{120} = \mathbf{109\ mA}$$

so that the collector current is

$$I_C = I_S - I_L = 109\text{ mA} - 89\text{ mA} = \mathbf{20\ mA}$$

(The current through the Zener and transistor base-emitter is smaller than I_C by the transistor beta.)

Improved Shunt Regulator The circuit of Fig. 15.23 shows an improved shunt voltage regulator circuit. The Zener diode provides a reference voltage so that the voltage across R_1 senses the output voltage. As the output voltage tries to change, the current shunted by transistor Q_1 is varied to maintain the output voltage constant. Transistor Q_2 provides a larger base current to transistor Q_1 than the circuit of Fig. 15.21, so that the regulator handles a larger load current. The output voltage is set by the Zener voltage and that across the two transistor base-emitters,

$$V_o = V_L = V_Z + V_{BE_2} + V_{BE_1} \tag{15.20}$$

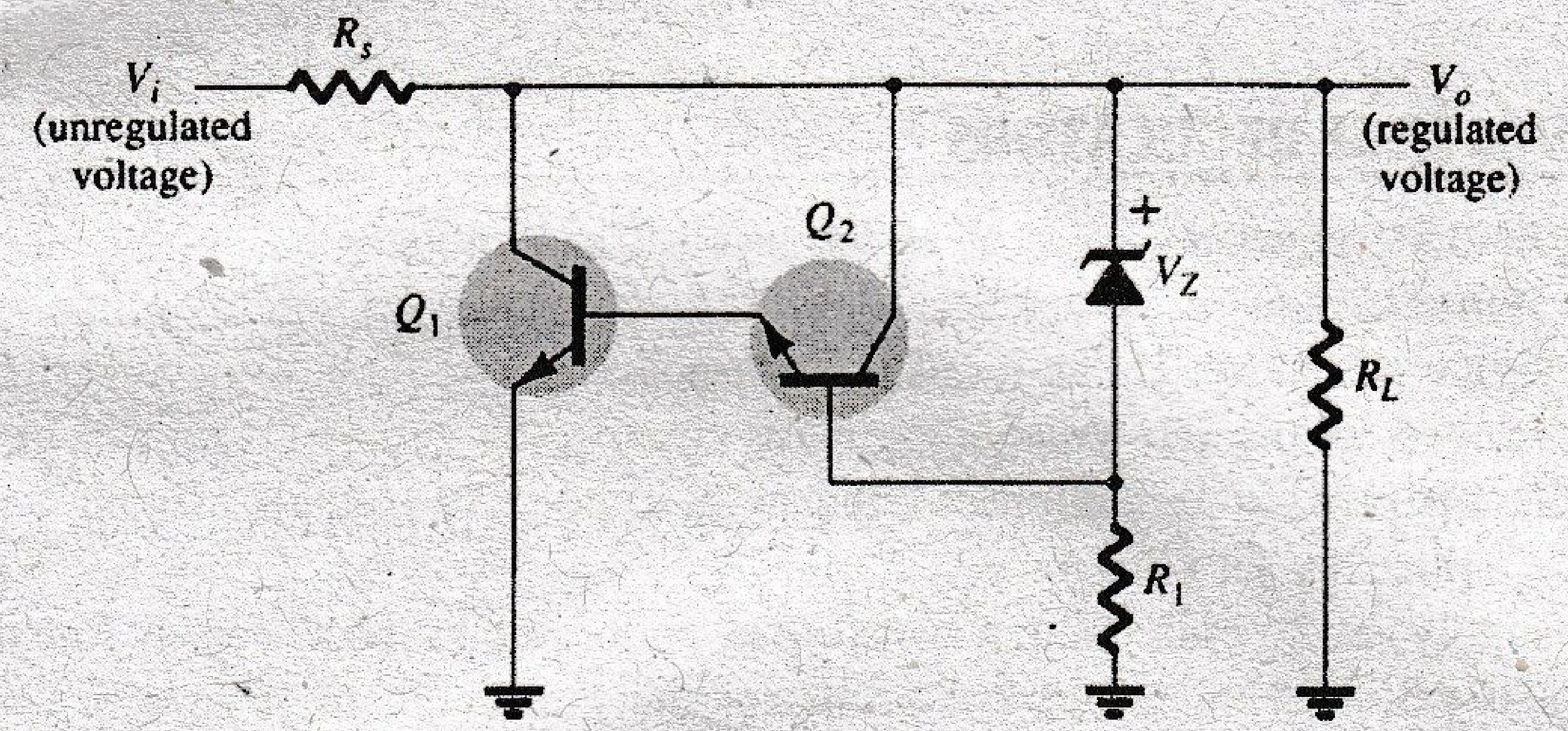


FIG. 15.23
Improved shunt voltage regulator circuit.

Shunt Voltage Regulator Using Op-Amp Figure 15.24 shows another version of a shunt voltage regulator using an op-amp as voltage comparator. The Zener voltage is compared to the feedback voltage obtained from voltage divider R_1 and R_2 to provide the control drive current to shunt element Q_1. The current through resistor R_S is thus controlled to drop a voltage across R_S so that the output voltage is maintained.

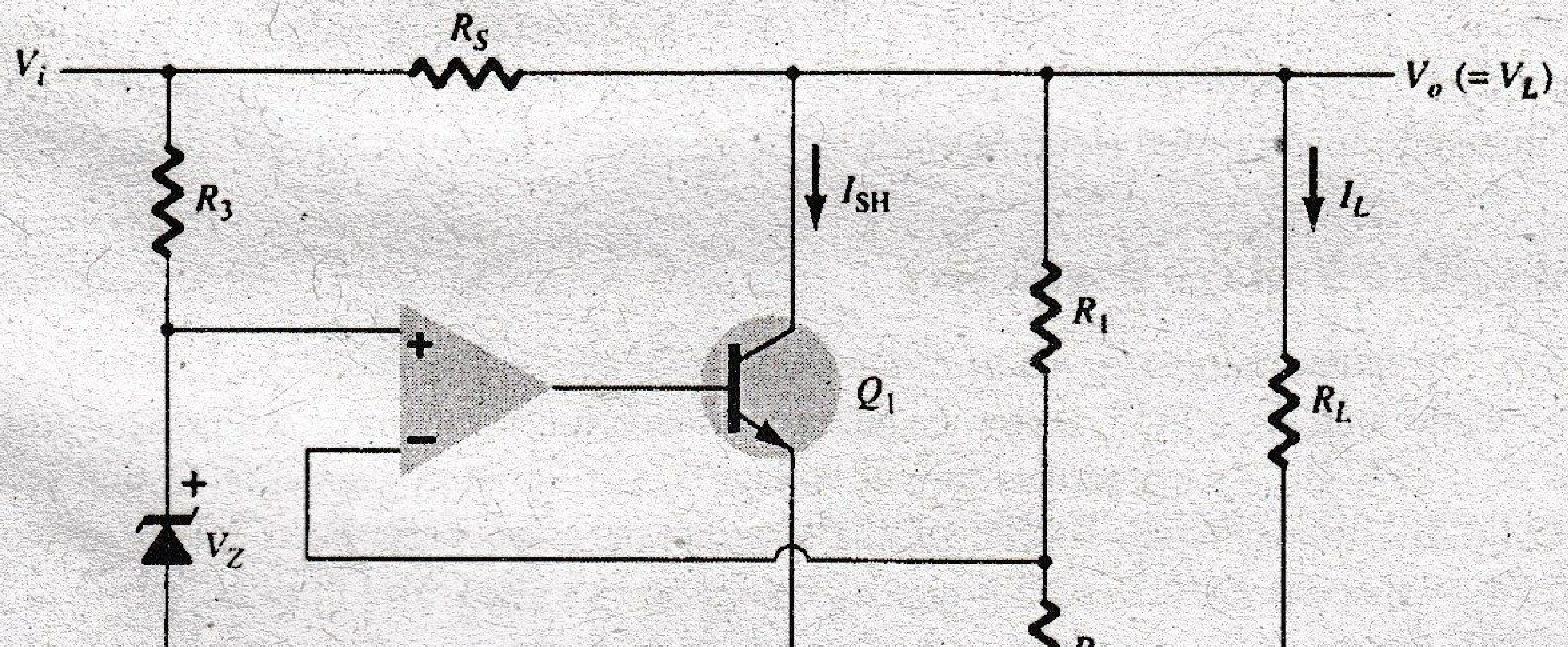


FIG. 15.24
Shunt voltage regulator using an op-amp.

Switching Regulation

A type of regulator circuit that is quite popular for its efficient transfer of pow
is the switching regulator. Basically, a switching regulator passes vol
pulses, which are then filtered to provide a smooth dc voltage. F
basic components of such a voltage regulator. The added circ
the improved operating efficiency obtained.

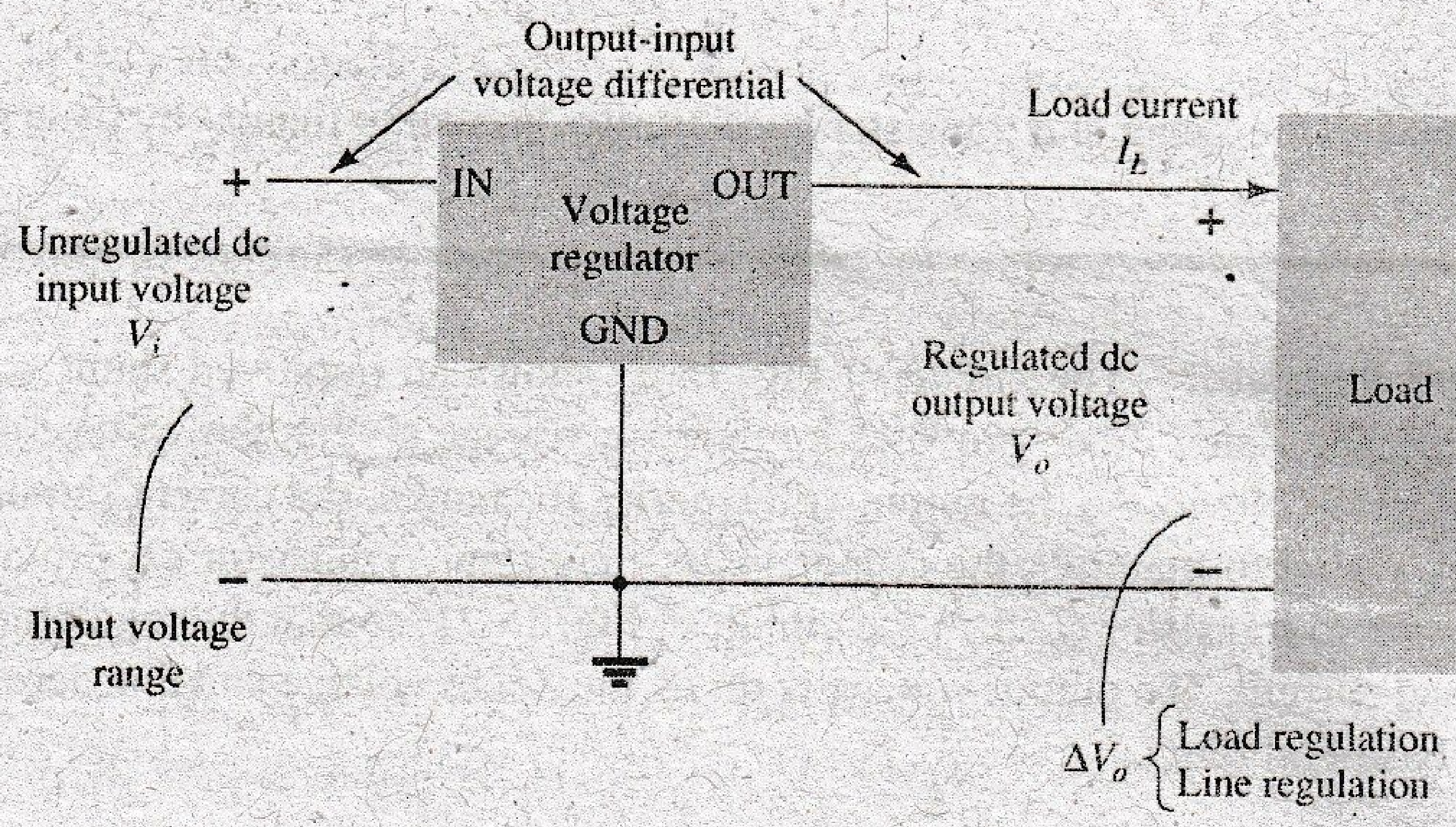


FIG. 15.25
Block representation of three-terminal voltage regulator.

15.6 IC VOLTAGE REGULATORS

Voltage regulators comprise a class of widely used ICs. Regulator IC units contain the circuitry for reference source, comparator amplifier, control device, and overload protection all in a single IC. Although the internal construction of the IC is somewhat different from that described for discrete voltage regulator circuits, the external operation is much the same. IC units provide regulation of either a fixed positive voltage, a fixed negative voltage, or an adjustably set voltage.

A power supply can be built using a transformer connected to the ac supply line to step the ac voltage to a desired amplitude, then rectifying that ac voltage, filtering with a capacitor and *RC* filter, if desired, and finally regulating the dc voltage using an IC regulator. The regulators can be selected for operation with load currents from hundreds of milliamperes to tens of amperes, corresponding to power ratings from milliwatts to tens of watts.

Three-Terminal Voltage Regulators

Figure 15.25 shows the basic connection of a three-terminal voltage regulator IC to a load. The fixed voltage regulator has an unregulated dc input voltage V_i applied to one input terminal, a regulated output dc voltage V_o from a second terminal, and the third terminal connected to ground. For a selected regulator, IC device specifications list a voltage range over which the input voltage can vary to maintain a regulated output voltage over a range of load current. The specifications also list the amount of output voltage change resulting from a change in load current (load regulation) or in input voltage (line regulation).

Fixed-Positive-Voltage Regulators

The series 78 regulators provide fixed regulated voltages from 5 V to 24 V. Figure 15.26 shows how one such IC, a 7812, is connected to provide voltage regulation with output from this unit of +12 V dc. An unregulated input voltage V_i is filtered by capacitor C_1 and connected to the IC's IN terminal. The IC's OUT terminal provides a regulated +12 V, which is filtered by capacitor C_2 (mostly for any high-frequency noise). The third IC terminal is connected to ground (GND). Whereas the input voltage may vary over some permissible

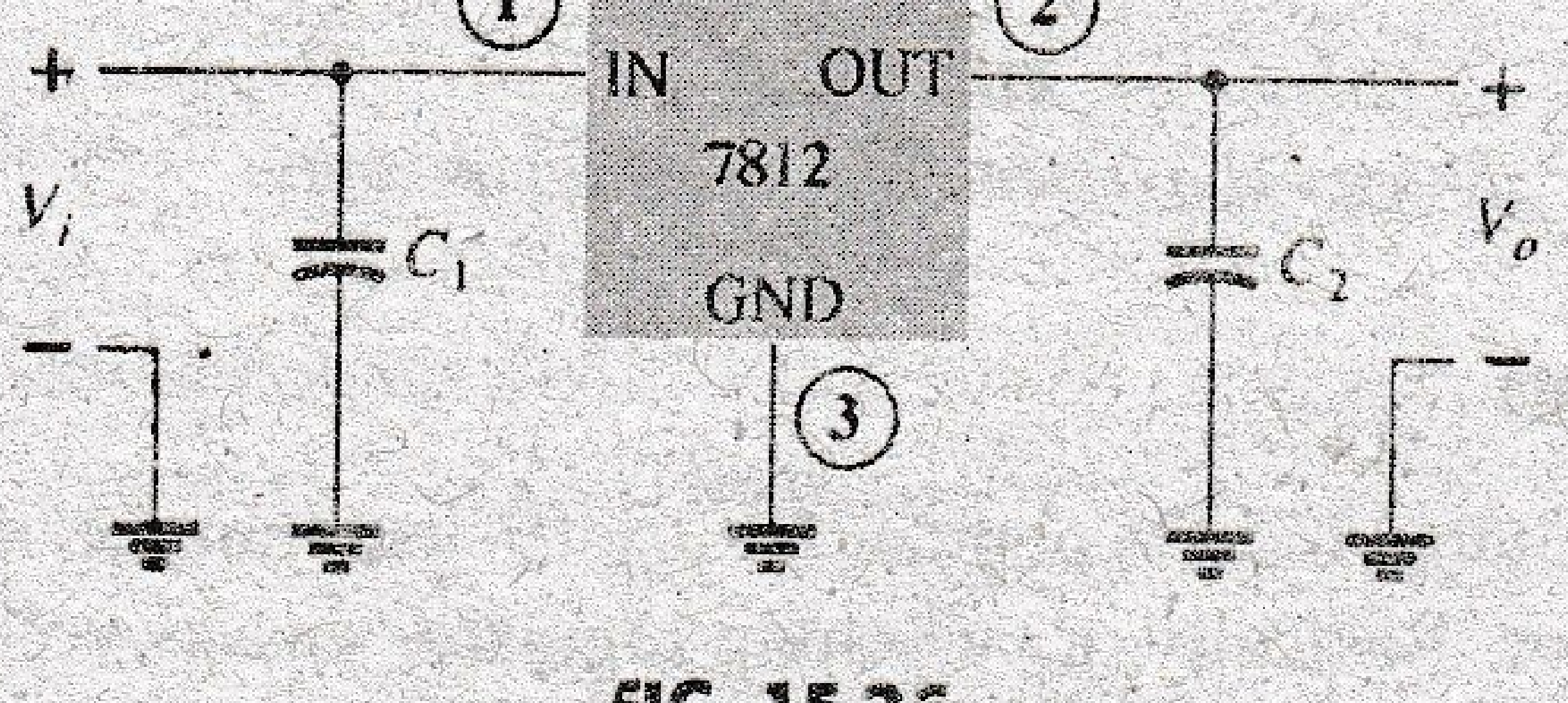


FIG. 15.26
Connection of a 7812 voltage regulator.

-52(B)

voltage range and the output load may vary over some acceptable range, the output voltage remains constant within specified voltage variation limits. These limitations are spelled out in the manufacturer's specification sheets. A table of positive-voltage regulator ICs is provided in Table 15.1.

TABLE 15.1
Positive-Voltage Regulators in the 7800 Series

IC Part	Output Voltage (V)	Minimum V_i (V)
7805	+5	7.3
7806	+6	8.3
7808	+8	10.5
7810	+10	12.5
7812	+12	14.6
7815	+15	17.7
7818	+18	21.0
7824	+24	27.1

The connection of a 7812 in a complete voltage supply is shown in the connection of Fig. 15.27. The ac line voltage (120 V rms) is stepped down to 18 V rms across each half of the center-tapped transformer. A full-wave rectifier and capacitor filter then provides an unregulated dc voltage, shown as a dc voltage of about 22 V, with ac ripple of a few volts as input to the voltage regulator. The 7812 IC then provides an output that is a regulated +12 V dc.

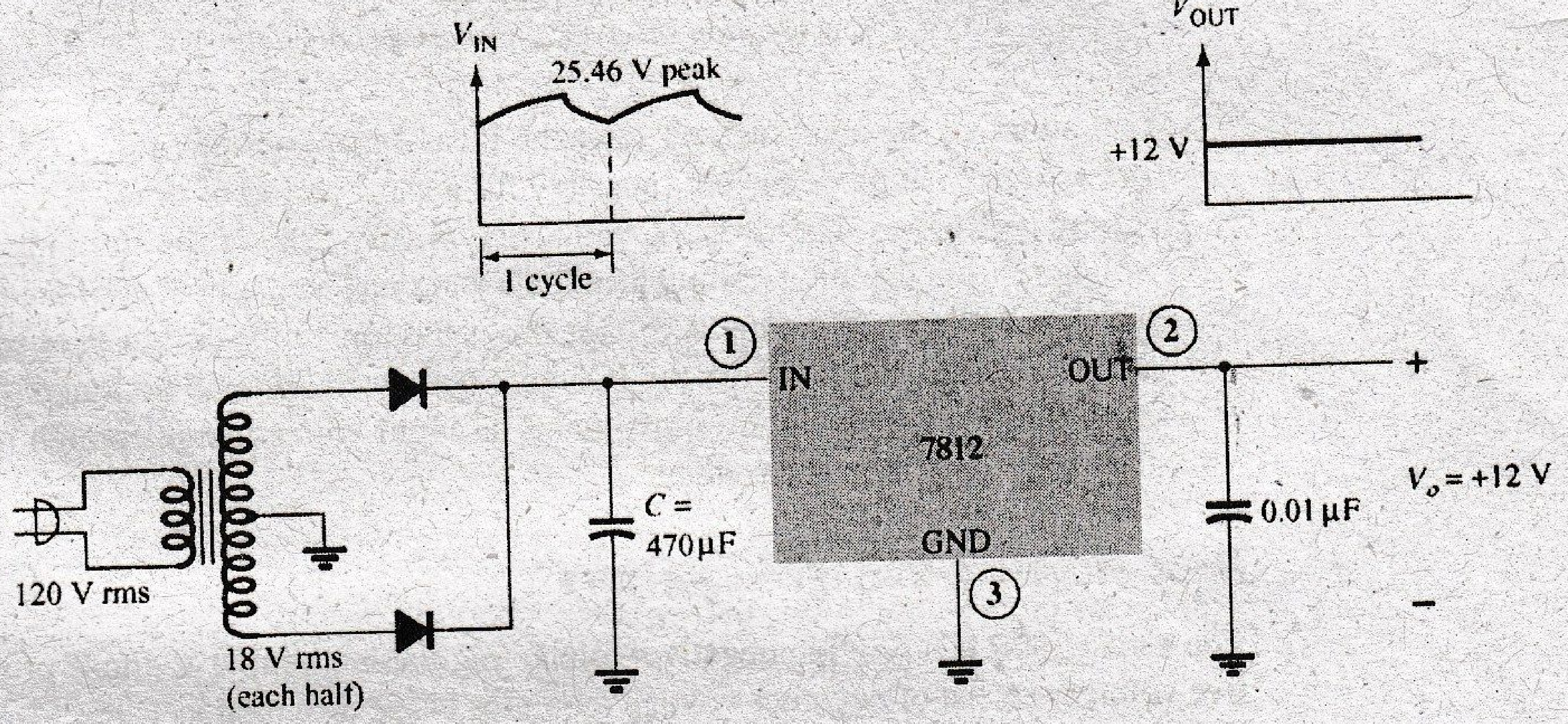


FIG. 15.27
A +12 V power supply.

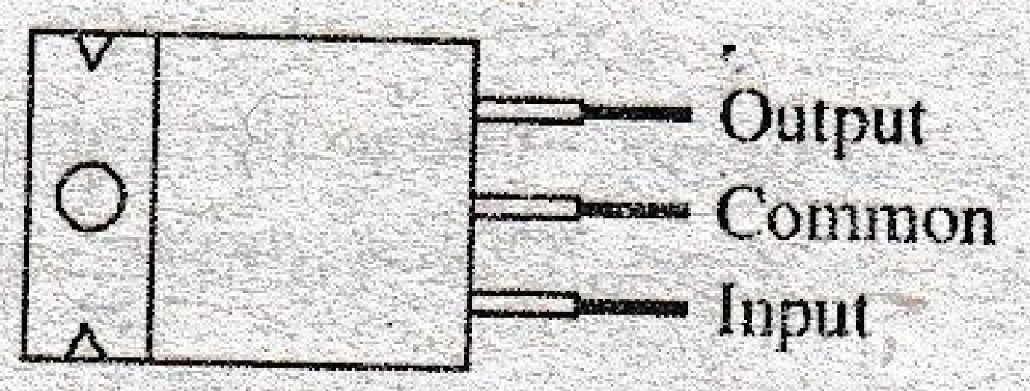
Positive-Voltage-Regulator Specifications The specifications sheet of voltage regulators is typified by that shown in Fig. 15.28 for the group of series 7800 positive-voltage regulators. Some consideration of a few of the more important parameters should be made.

Output voltage: The specification for the 7812 shows that the output voltage is typically +12 V but could be as low as 11.5 V or as high as 12.5 V.

Output regulation: The output voltage regulation is seen to be typically 4 mV, to a maximum of 100 mV (at output currents from 0.25 A to 0.75 A). This information specifies that the output voltage can typically vary only 4 mV from the rated 12 V dc.

Short-circuit output current: The amount of current is limited to typically 0.35 A if the output were to be short-circuited (presumably by accident or by another faulty component).

Peak output current: Although the rated maximum current is 1.5 A for this series of IC, the typical peak output current that might be drawn by a load is 2.2 A. This shows



Nominal output voltage	Regulator
5 V	7805
6 V	7806
8 V	7808
10 V	7810
12 V	7812
15 V	7815
18 V	7818
24 V	7824

Absolute maximum ratings:

Input voltage	40 V
Continuous total dissipation	2 W
Operating free-air temperature range	−65 to 150°C

µA 7812C electrical characteristics:

Parameter	Min.	Typ.	Max.	Units
Output voltage	11.5	12	12.5	V
Input regulation		3	120	mV
Ripple rejection	55	71		dB
Output regulation		4	100	mV
Output resistance		0.018		Ω
Dropout voltage		2.0		V
Short-circuit output current		350		mA
Peak output current		2.2		A

FIG. 15.28
Specification sheet data for voltage regulator ICs.

that although the manufacturer rates the IC as capable of providing 1.5 A, one could draw somewhat more current (possibly for a short period of time).

Dropout voltage: The dropout voltage, typically 2 V, is the minimum amount of voltage across the input–output terminals that must be maintained if the IC is to operate as a regulator. If the input voltage drops too low or the output rises so that at least 2 V is not maintained across the IC input–output, the IC will no longer provide voltage regulation. One therefore maintains an input voltage large enough to assure that the dropout voltage is provided.

Fixed-Negative-Voltage Regulators

The series 7900 ICs provide negative-voltage regulators, similar to those providing positive voltages. A list of negative-voltage regulator ICs is provided in Table 15.2. As shown, IC regulators are available for a range of fixed negative voltages, the selected IC providing the rated output voltage as long as the input voltage is maintained greater than the minimum input value. For example, the 7912 provides an output of −12 V as long as the input to the regulator IC is more negative than −14.6 V.

TABLE 15.2
Negative-Voltage Regulators in 7900 Series

IC Part	Output Voltage (V)	Minimum V_i (V)
7905	−5	−7.3
7906	−6	−8.4
7908	−8	−10.5
7909	−9	−11.5
7912	−12	−14.6
7915	−15	−17.7
7918	−18	−20.8
7924	−24	−27.1

EXAMPLE 15.12 Draw a voltage supply using a full-wave bridge rectifier, capacitor filter, and IC regulator to provide an output of +5 V.

Solution: The resulting circuit is shown in Fig. 15.29.

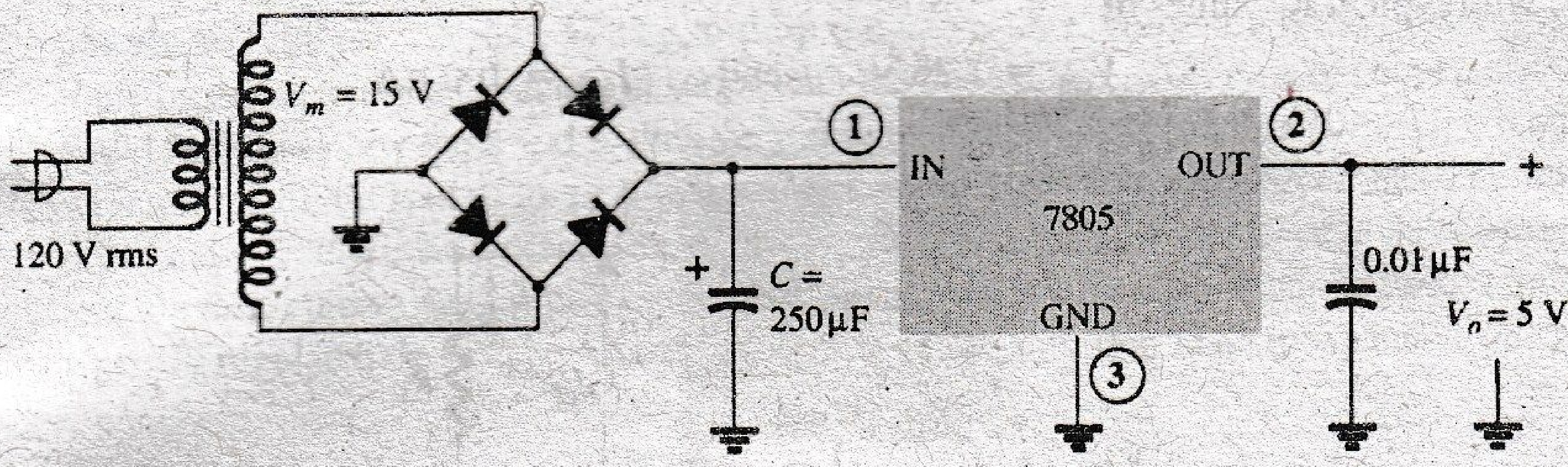


FIG. 15.29
A +5-V power supply.

EXAMPLE 15.13 For a transformer output of 15 V and a filter capacitor of 250 μF, calculate the minimum input voltage when connected to a load drawing 400 mA.

Solution: The voltages across the filter capacitor are

$$V_r(\text{peak}) = \sqrt{3}\,V_r(\text{rms}) = \sqrt{3}\,\frac{2.4I_{\text{dc}}}{C} = \sqrt{3}\,\frac{2.4(400)}{250} = 6.65\text{ V}$$

$$V_{\text{dc}} = V_m - V_r(\text{peak}) = 15\text{ V} - 6.65\text{ V} = 8.35\text{ V}$$

Since the input swings around this dc level, the minimum input voltage can drop to as low as

$$V_i(\text{low}) = V_{\text{dc}} - V_r(\text{peak}) = 15\text{ V} - 6.65\text{ V} = \mathbf{8.35\text{ V}}.$$

Since this voltage is greater than the minimum required for the IC regulator (from Table 15.1, $V_i = 7.3$ V), the IC can provide a regulated voltage to the given load.

EXAMPLE 15.14 Determine the maximum value of load current at which regulation is maintained for the circuit of Fig. 15.29.

Solution: To maintain $V_i(\text{min}) \geq 7.3$ V,

$$V_r(\text{peak}) \leq V_m - V_i(\text{min}) = 15\text{ V} - 7.3\text{ V} = 7.7\text{ V}$$

so that

$$V_r(\text{rms}) = \frac{V_r(\text{peak})}{\sqrt{3}} = \frac{7.7\text{ V}}{1.73} = 4.4\text{ V}$$

The value of load current is then

$$I_{\text{dc}} = \frac{V_r(\text{rms})C}{2.4} = \frac{(4.4\text{ V})(250)}{2.4} = \mathbf{458\text{ mA}}$$

Any current above this value is too large for the circuit to maintain the regulator output at +5 V.

Adjustable-Voltage Regulators

Voltage regulators are also available in circuit configurations that allow the user to set the output voltage to a desired regulated value. The LM317, for example, can be operated with the output voltage regulated at any setting over the range of voltage from 1.2 V to 37 V. Figure 15.30 shows how the regulated output voltage of an LM317 can be set.

Resistors R_1 and R_2 set the output to any desired voltage over the adjustment range (1.2 V to 37 V). The output voltage desired can be calculated using

$$V_o = V_{\text{ref}}\left(1 + \frac{R_2}{R_1}\right) + I_{\text{adj}}R_2 \tag{15.21}$$

with typical IC values of

$$V_{\text{ref}} = 1.25\text{ V} \qquad \text{and} \qquad I_{\text{adj}} = 100\ \mu\text{A}$$

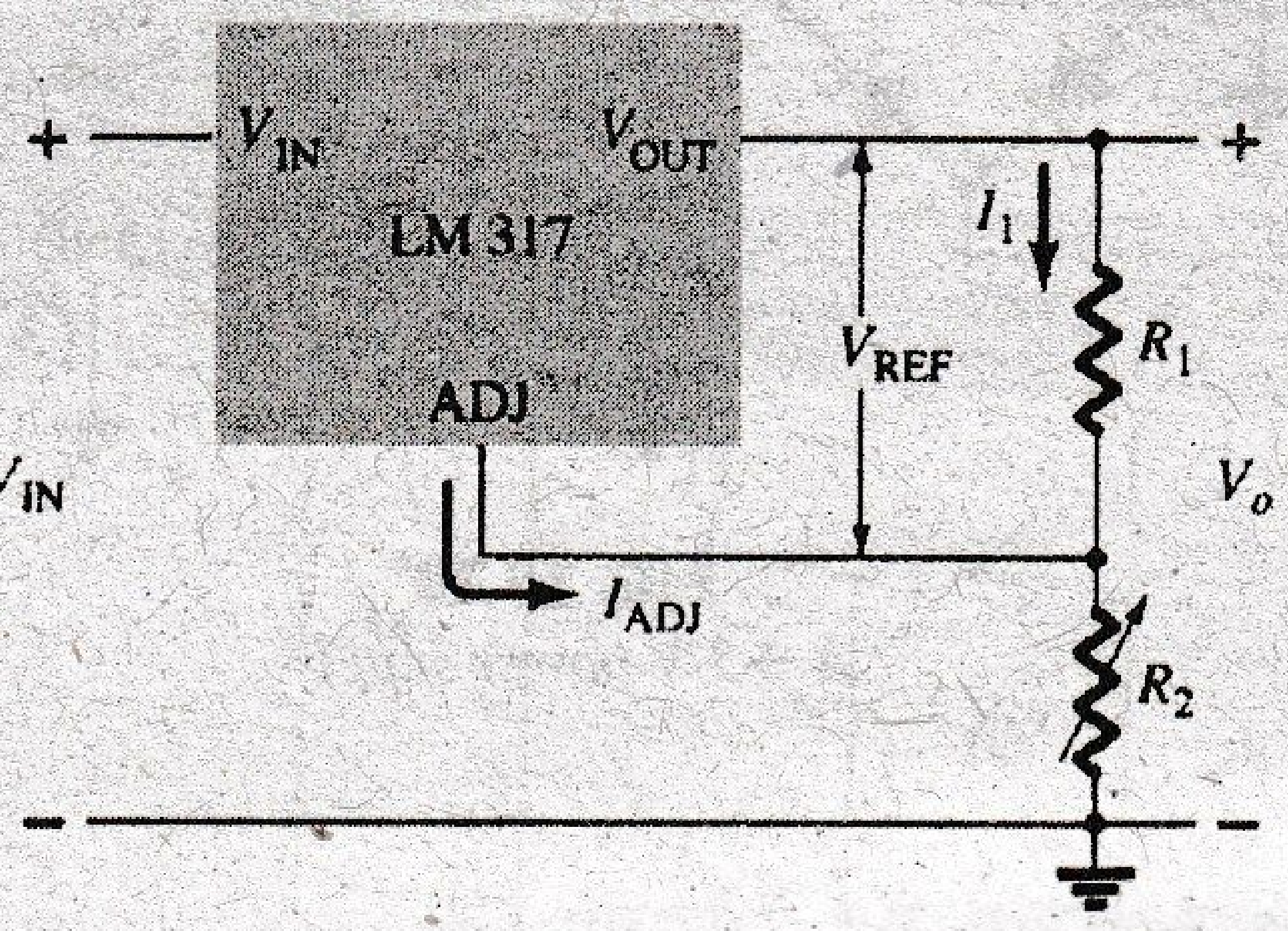


FIG. 15.30
Connection of LM317 adjustable-voltage regulator.

EXAMPLE 15.15 Determine the regulated voltage in the circuit of Fig. 15.30 with $R_1 = 240\ \Omega$ and $R_2 = 2.4\text{ k}\Omega$.

Solution:

$$\text{Eq. (15.21):}\quad V_o = 1.25\text{ V}\left(1 + \frac{2.4\text{ k}\Omega}{240\ \Omega}\right) + (100\ \mu\text{A})(2.4\text{ k}\Omega)$$
$$= 13.75\text{ V} + 0.24\text{ V} = \mathbf{13.99\text{ V}}$$

EXAMPLE 15.16 Determine the regulated output voltage of the circuit in Fig. 15.31.

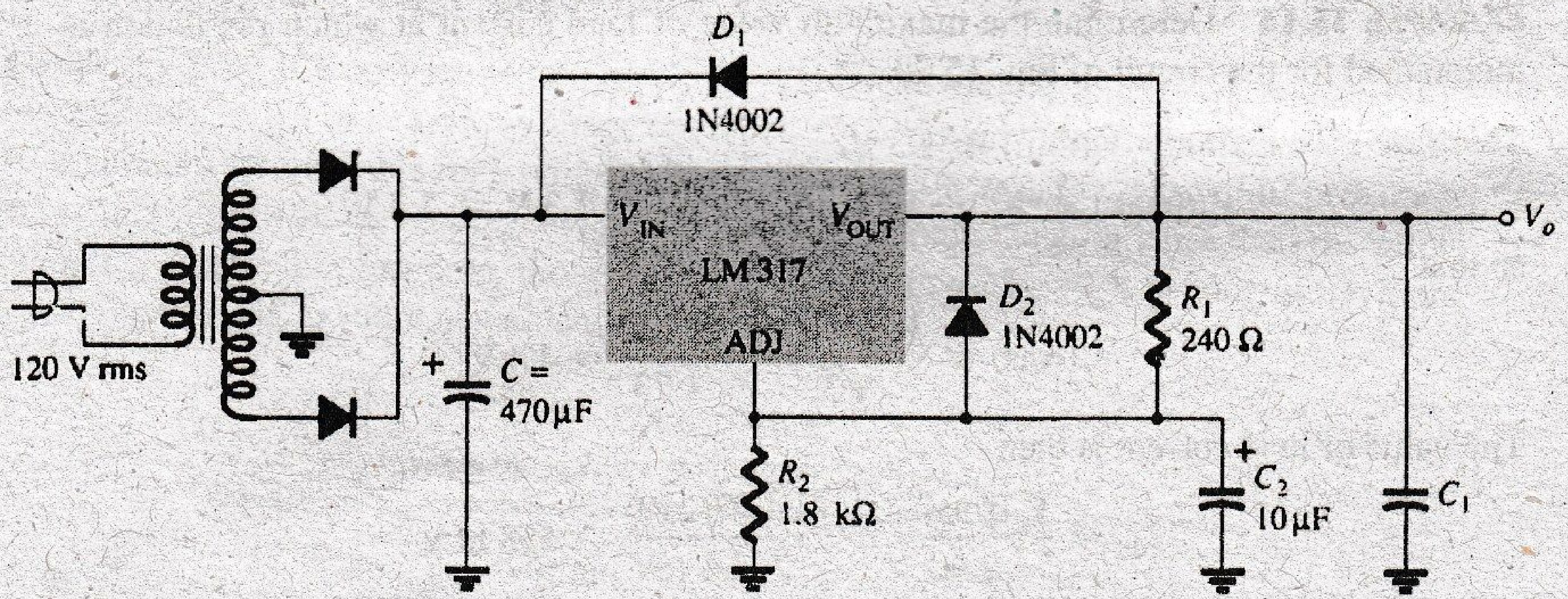


FIG. 15.31
Positive adjustable-voltage regulator for Example 15.16.

Solution: The output voltage calculated using Eq. (15.21) is

$$V_o = 1.25\text{ V}\left(1 + \frac{1.8\text{ k}\Omega}{240\ \Omega}\right) + (100\ \mu\text{A})(1.8\text{ k}\Omega) \approx \mathbf{10.8\text{ V}}$$

A check of the filter capacitor voltage shows that an input–output difference of 2 V can be maintained up to at least 200 mA load current.

15.7 PRACTICAL APPLICATIONS

Power Supplies

Power supplies are a part of every electronic device, so a wide variety of circuits are used to accommodate such factors as power rating, size of circuit, cost, desired regulation, and so on. This section will outline a number of practical supplies and chargers.

Simple DC Supply A simple way to drop the ac voltage, without a bulky and expensive transformer, is to use a capacitor in series with the line voltage. This type of supply, shown in Fig. 15.32, uses few parts and is thus very simple. A half-wave rectifier (or bridge rectifier) with a filter circuit is used to get a voltage with a dc component. This circuit has a number of drawbacks: There is no isolation from the ac line, a minimal current must always be drawn, and the load current cannot be excessive. Thus, the simple dc supply can be used to provide a poorly regulated dc voltage when light current draw is desired in an inexpensive device.

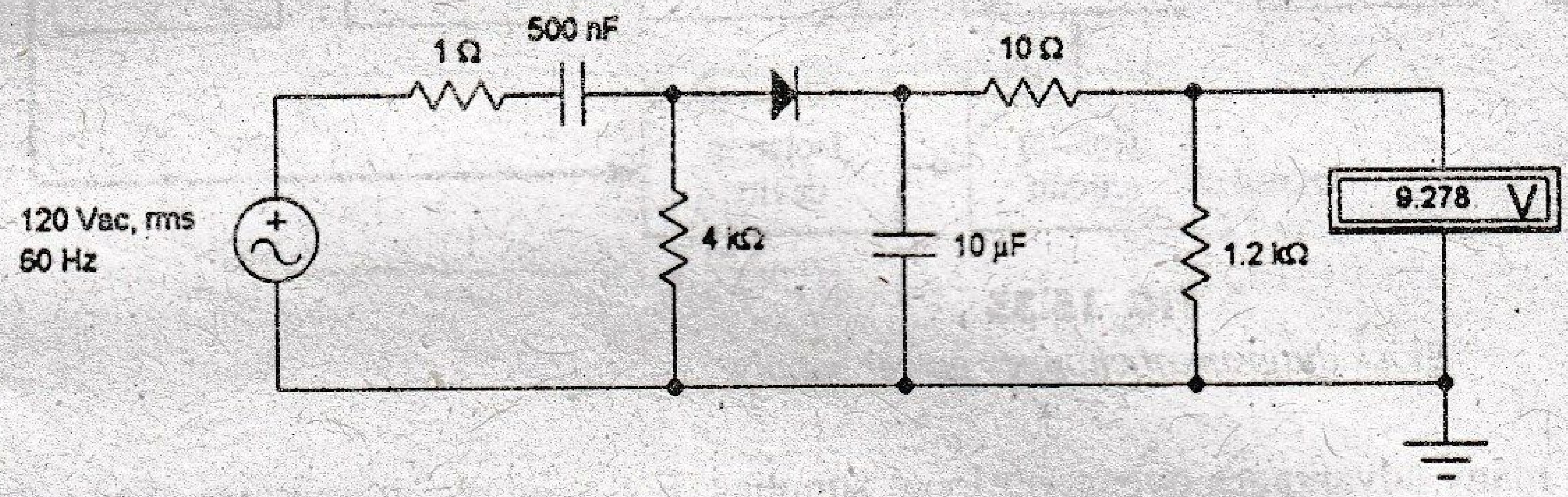


FIG. 15.32
Simple dc supply.

DC Supply with Transformer Input The next type of power supply uses a transformer to step down the ac line voltage. The transformer can be either a wall mount (external) or a chassis mount (internal). A rectifier is used after the transformer, followed by a capacitor filter and possibly a regulator. The regulator becomes a problem as the power requirements increase. Heat sink size, cooling, and power requirements become a major obstacle to these types of supplies.

Figure 15.33 shows a simple half-wave rectified supply with an isolating step-down transformer. This relatively simple circuit provides no regulation.

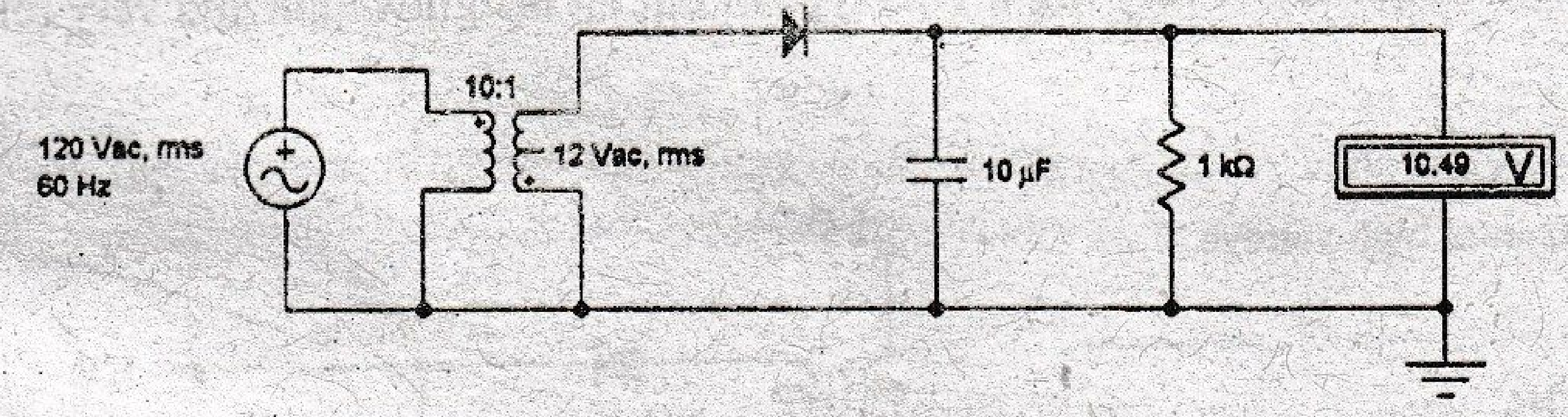


FIG. 15.33
DC supply with transformer input.

Figure 15.34 shows probably the best standard power supply—with transformer isolation and voltage step-down; a bridge rectifier; a dual filter with choke; and a regulator circuit made of a Zener reference, a parallel regulation transistor, and an op-amp with feedback to aid the regulation. This circuit obviously provides excellent voltage regulation.

Chopper Supply Today's power supplies convert ac to dc using a chopper circuit such as that shown in Fig. 15.35. The ac input is connected to the circuit through various line conditioners and filters. This removes any electrical noise. The input is then rectified and lightly filtered. The high dc voltage is chopped at a rate of approximately 100 kHz. The rate and the duration of the chopping are controlled by a special-function integrated circuit. An isolation transformer couples the chopped dc to a filtering and rectifying circuit. The output of the power supply is fed back to the control integrated circuit. By monitoring the output, the IC can regulate the output voltage. Although this type of power supply is more complicated, it

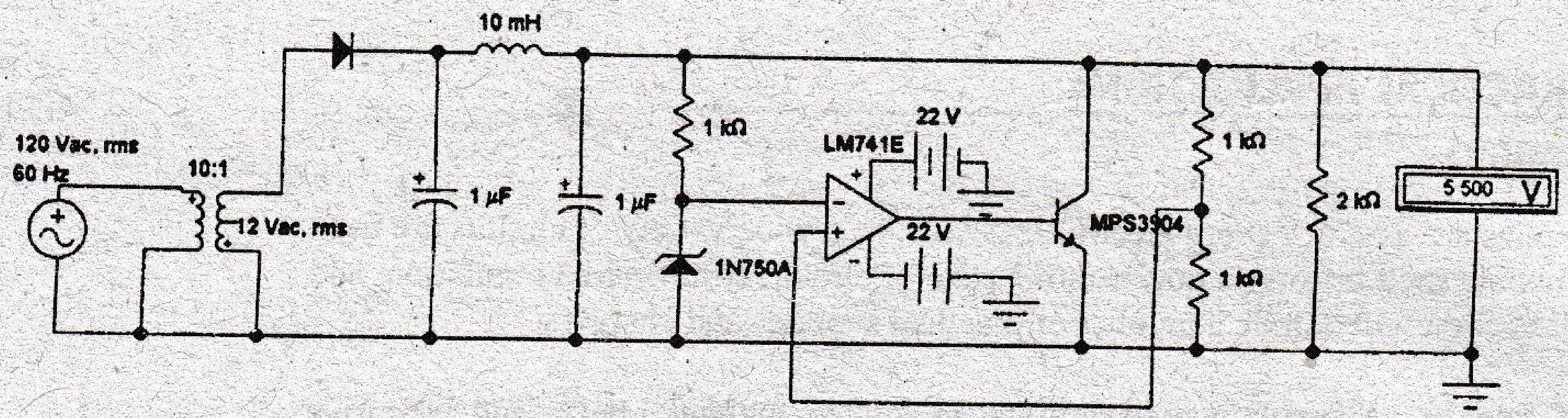


FIG. 15.34
Series-regulated supply with transformer input and IC regulation.

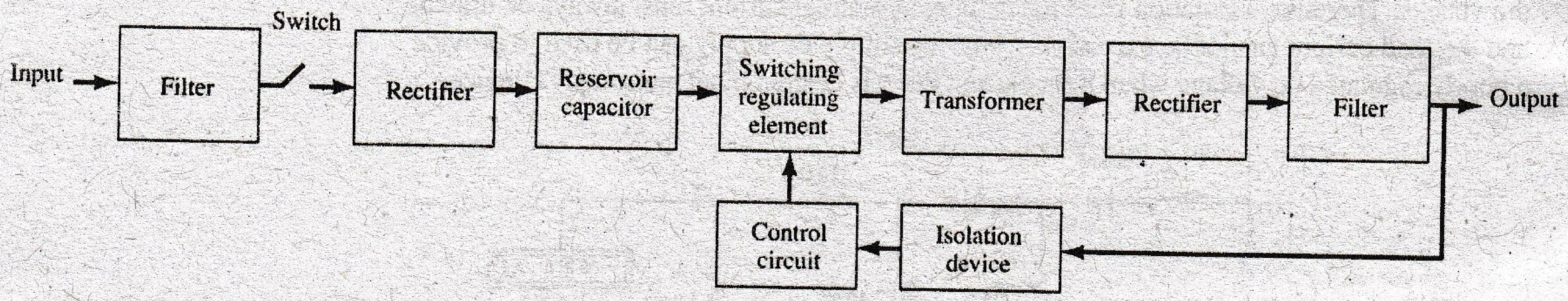


FIG. 15.35
Block diagram of chopper power supply.

has many advantages over traditional supplies. For example, it operates over a very large range of input ac voltages, it operates independently of the input frequency, it can be made very small, and it operates over a large range of current demands and low heat dissipation.

Special TV Horizontal High-Voltage Supply Television sets require a very high dc voltage to operate the picture tube (cathode ray tube, CRT). In early TV sets this voltage was supplied by a high-voltage transformer with very high voltage rated capacitors. The circuit was very bulky, heavy, and dangerous. TV sets utilize two basic frequencies to scan the screen: 60 Hz (vertical oscillator) and 15 kHz (horizontal oscillator). Using the horizontal oscillator, one can build a high-voltage dc supply. The circuit is known as a *flyback power supply* (see Fig. 15.36). The low dc voltage is pulsed into a small flyback transformer. The flyback transformer is a step-up autotransformer. The output is rectified and filtered with a small-value capacitor. The flyback transformer can be small, and the filter capacitor can be a small, low-value unit, because the frequency is very high. This type of circuit is lightweight and very reliable.

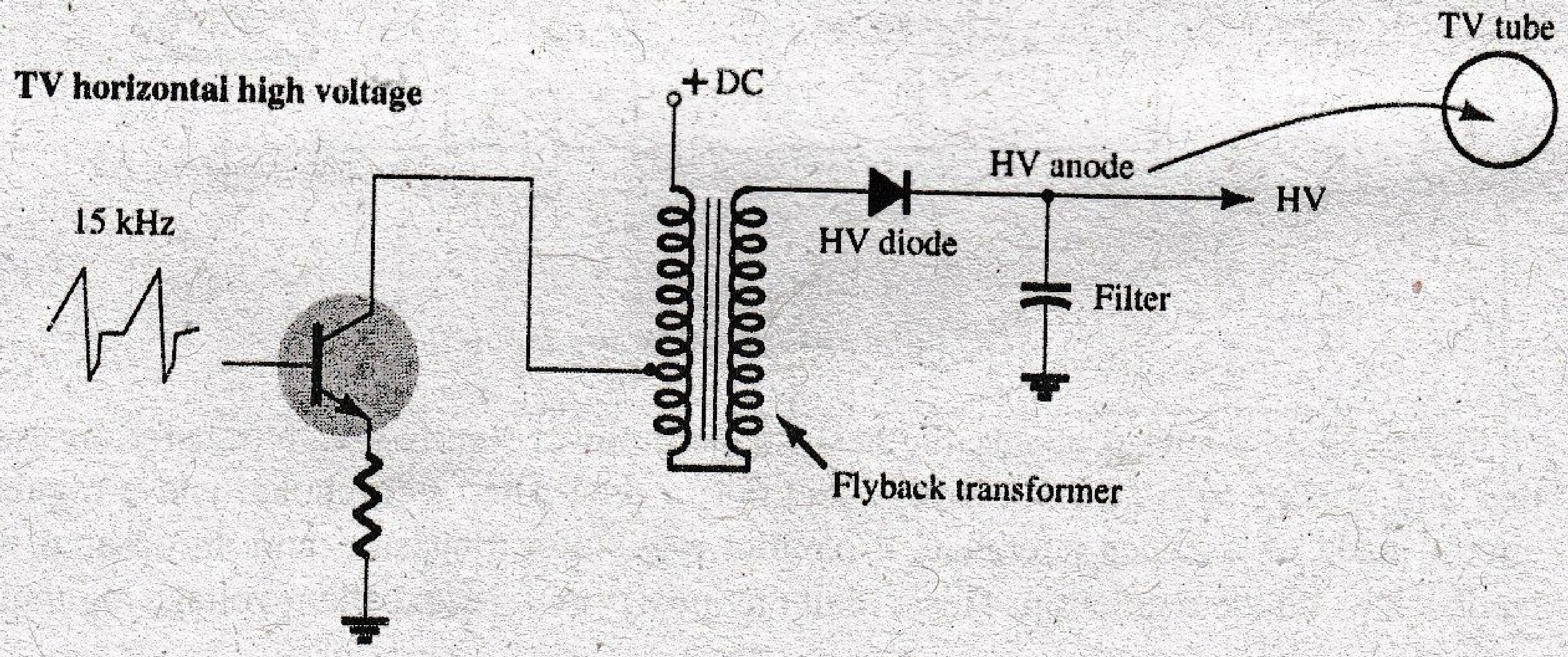


FIG. 15.36
TV horizontal high-voltage supply.

Battery Charger Circuits Battery charger circuits employ variations of the power supply circuits mentioned above. Figure 15.37a shows the basics of a simple charging circuit using a transformer setting with a selector switch to determine the charge rate current provided. For NiCad batteries the voltage that supplies the battery must be greater than the

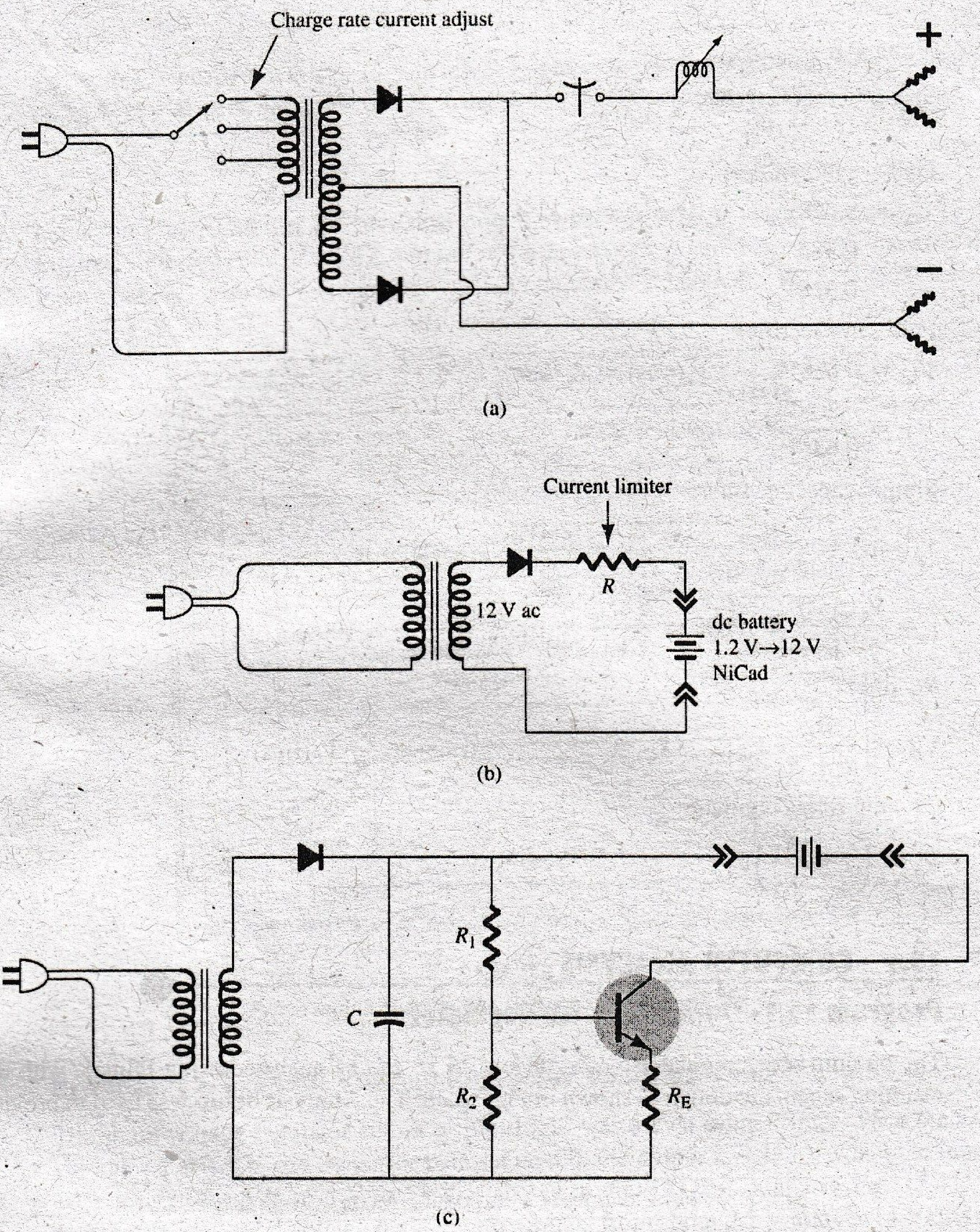


FIG. 15.37

Battery charger circuits: (a) Single charging circuit; (b) typical NiCad charging circuit; (c) lead–acid charging circuit.

battery being charged. The current must also be controlled and limited. Figure 15.37b shows a typical NiCad charging circuit. For a lead–acid battery, the voltage must be controlled so as not to exceed the battery's rated voltage. The charge current is determined by the power supply's capability, the power rating of the battery, and the amount of charge required. Figure 15.37c shows a simple lead–acid charging circuit.

Batteries can be charged using traditional dc supplies or from more elaborate chopper supplies. The major problem with charging batteries is determining when the battery is completely charged. Many exotic circuits exist to check the battery status.

15.8 SUMMARY

Equations

Ripple:

$$r = \frac{\text{ripple voltage (rms)}}{\text{dc voltage}} = \frac{V_r(\text{rms})}{V_{dc}} \times 100\%$$

Voltage regulation:

$$\%\text{V.R.} = \frac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}} \times 100\%$$

Half-wave rectifier:

$$V_{\text{dc}} = 0.318V_m, \qquad V_r(\text{rms}) = 0.385V_m$$

$$r = \frac{0.385V_m}{0.318V_m} \times 100\% = 121\%$$

Full-wave rectifier:

$$V_{\text{dc}} = 0.636V_m, \qquad V_r(\text{rms}) = 0.308V_m$$

$$r = \frac{0.308V_m}{0.636V_m} \times 100\% = 48\%$$

Simple capacitor filter:

$$V_r(\text{rms}) = \frac{I_{\text{dc}}}{4\sqrt{3}fC} = \frac{2.4I_{\text{dc}}}{C} = \frac{2.4V_{\text{dc}}}{R_LC}, \qquad V_{\text{dc}} = V_m - \frac{I_{\text{dc}}}{4fC} = \frac{4.17I_{dc}}{C}$$

$$r = \frac{V_r(\text{rms})}{V_{\text{dc}}} \times 100\% = \frac{2.4I_{\text{dc}}}{CV_{\text{dc}}} \times 100\% = \frac{2.4}{R_LC} \times 100\%$$

RC filter:

$$V'_{\text{dc}} = \frac{R_L}{R + R_L}V_{\text{dc}}, \qquad X_C = \frac{1.3}{C}, \qquad V'_r(\text{rms}) = \frac{X_C}{R}V_r(\text{rms})$$

Op-amp series regulator:

$$V_o = \left(1 + \frac{R_1}{R_2}\right)V_Z$$

15.9 COMPUTER ANALYSIS

Program 15.1—Op-Amp Series Regulator

The op-amp series regulator circuit of Fig. 15.16 can be analyzed using PSpice, with the resulting schematic drawn as shown in Fig. 15.38. The **Analysis Setup** was used to provide

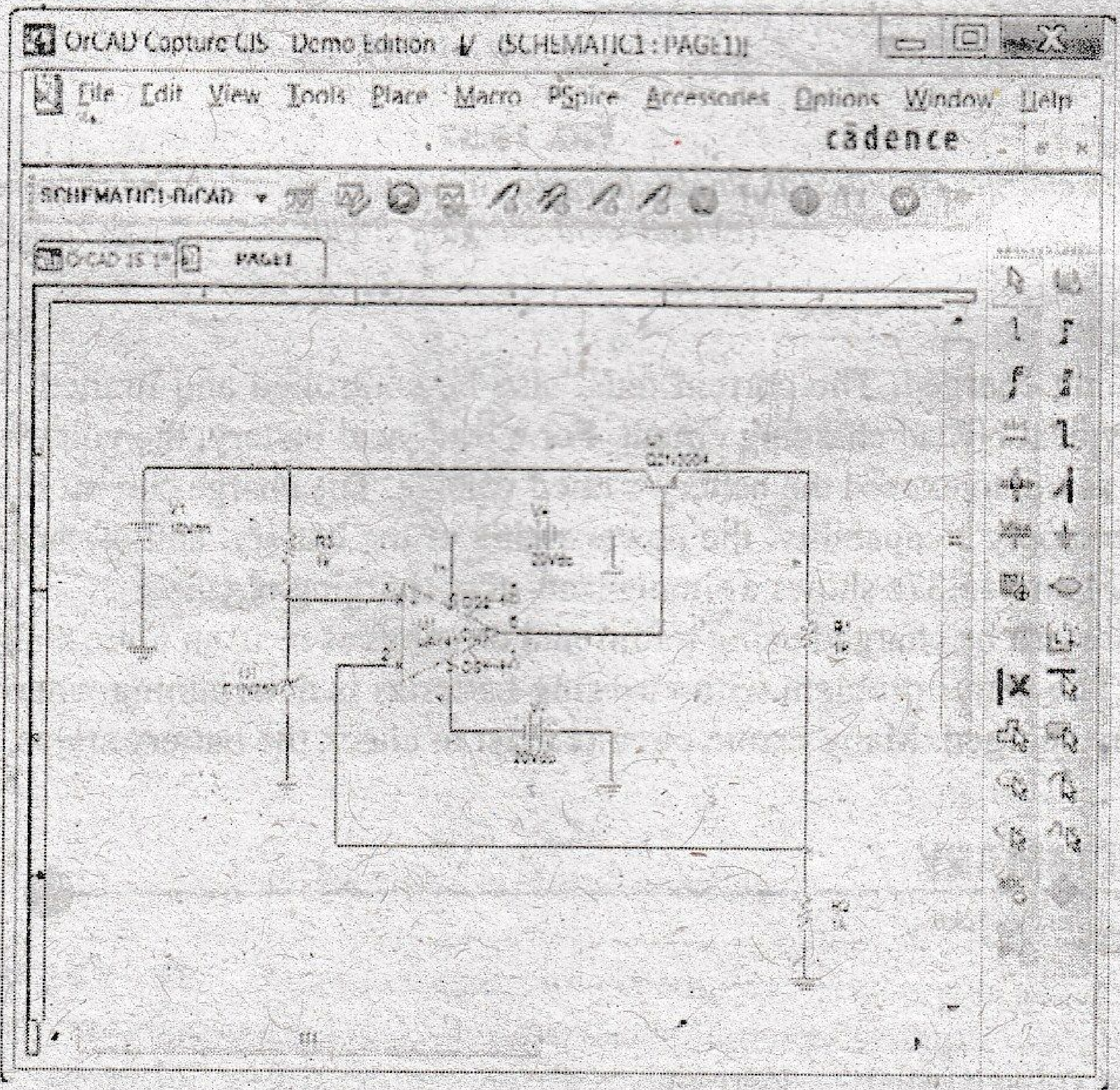


FIG. 15.38
Op-amp series regulator using PSpice.

a dc voltage sweep from 8 V to 15 V in 0.5-V increments. Diode D_1 provides a Zener voltage of 4.7 V ($V_Z = 4.7$), and transistor Q_1 is set to beta = 100. Using Eq. (15.18), we obtain

$$V_o = \left(1 + \frac{R_1}{R_2}\right)V_Z = \left(1 + \frac{1\text{ k}\Omega}{1\text{ k}\Omega}\right)4.7\text{ V} = 9.4\text{ V}$$

Notice in Fig. 15.38 that the regulated output voltage is 9.25 V when the input is 10 V. Figure 15.39 shows the **PROBE** output for the dc voltage sweep. Notice also that after the input goes above about 9 V, the output is held regulated at about 9.3 V.

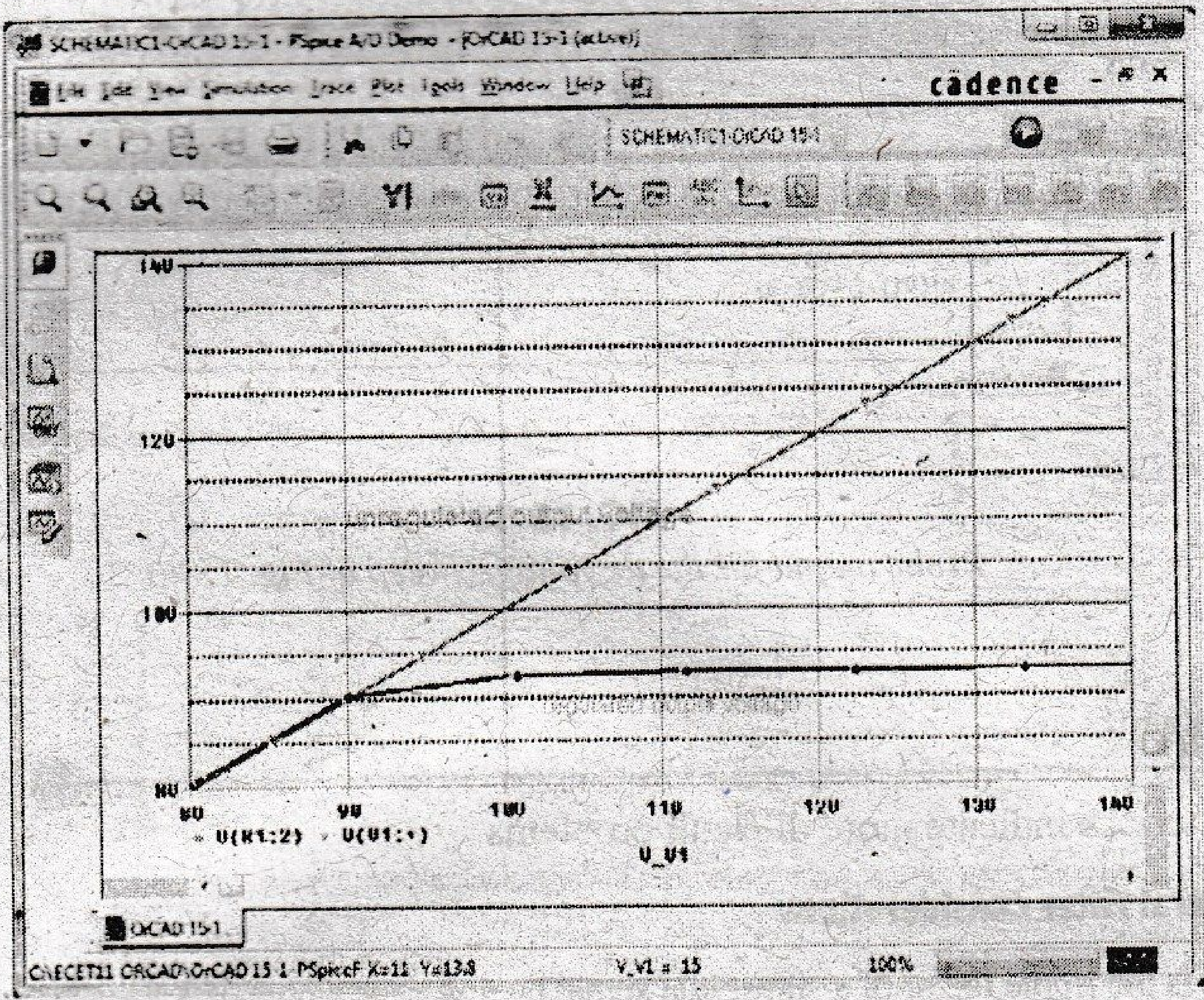


FIG. 15.39

Probe output showing the voltage regulation of Fig. 15.38.

Program 15.2—Shunt Voltage Regulator Using Op-Amp

The shunt voltage regulator circuit of Fig. 15.40 was drawn using PSpice. With the Zener voltage set at 4.7 V and transistor beta set at 100, the output is 9.255 V when the input is 10 V. A dc sweep from 8 V to 15 V is shown in the **PROBE** output in Fig. 15.41. The circuit provides good voltage regulation for inputs from about 9.5 V to over 14 V, the output being held at the regulated value of about 9.3 V.

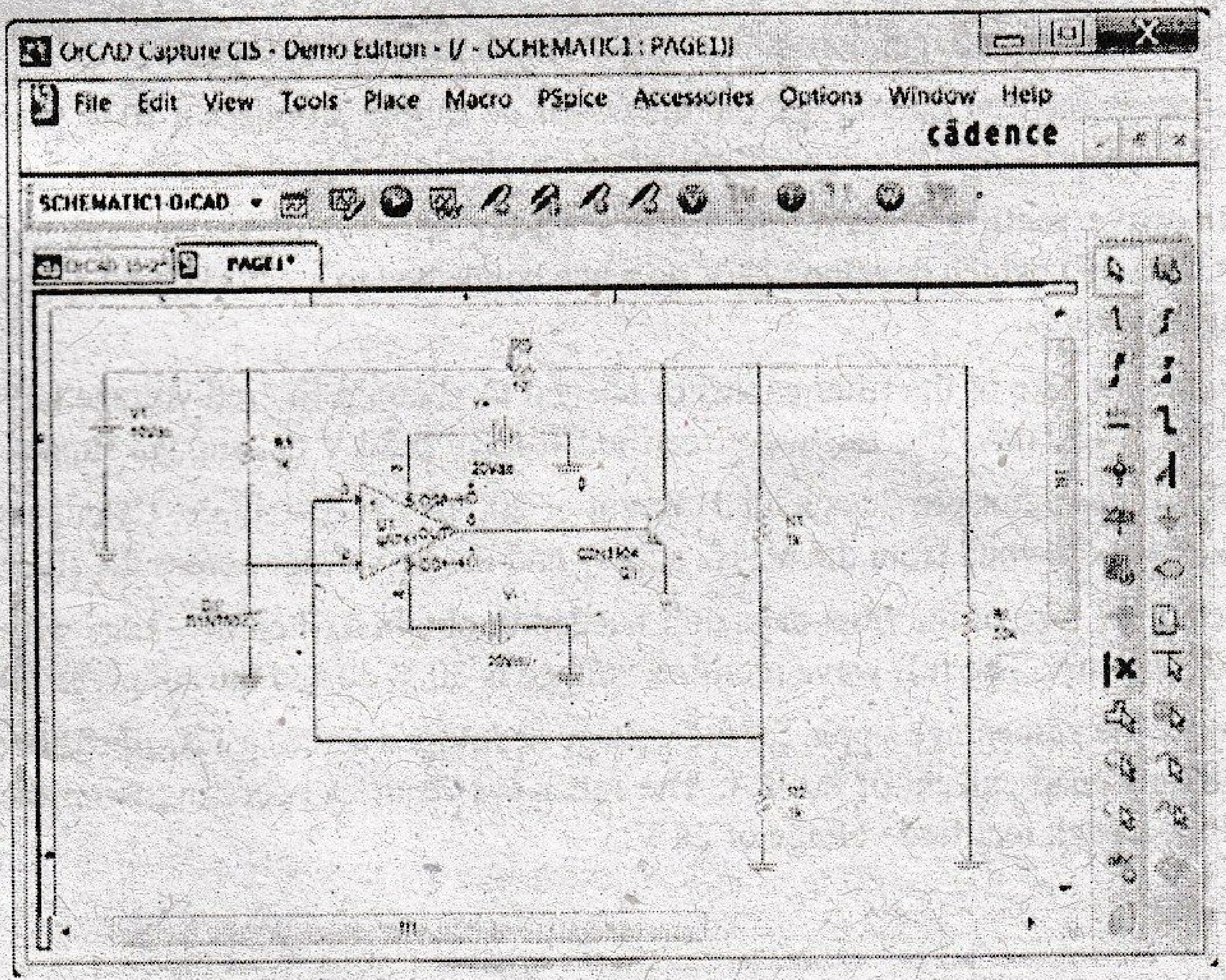


FIG. 15.40

Shunt voltage regulator using an op-amp.

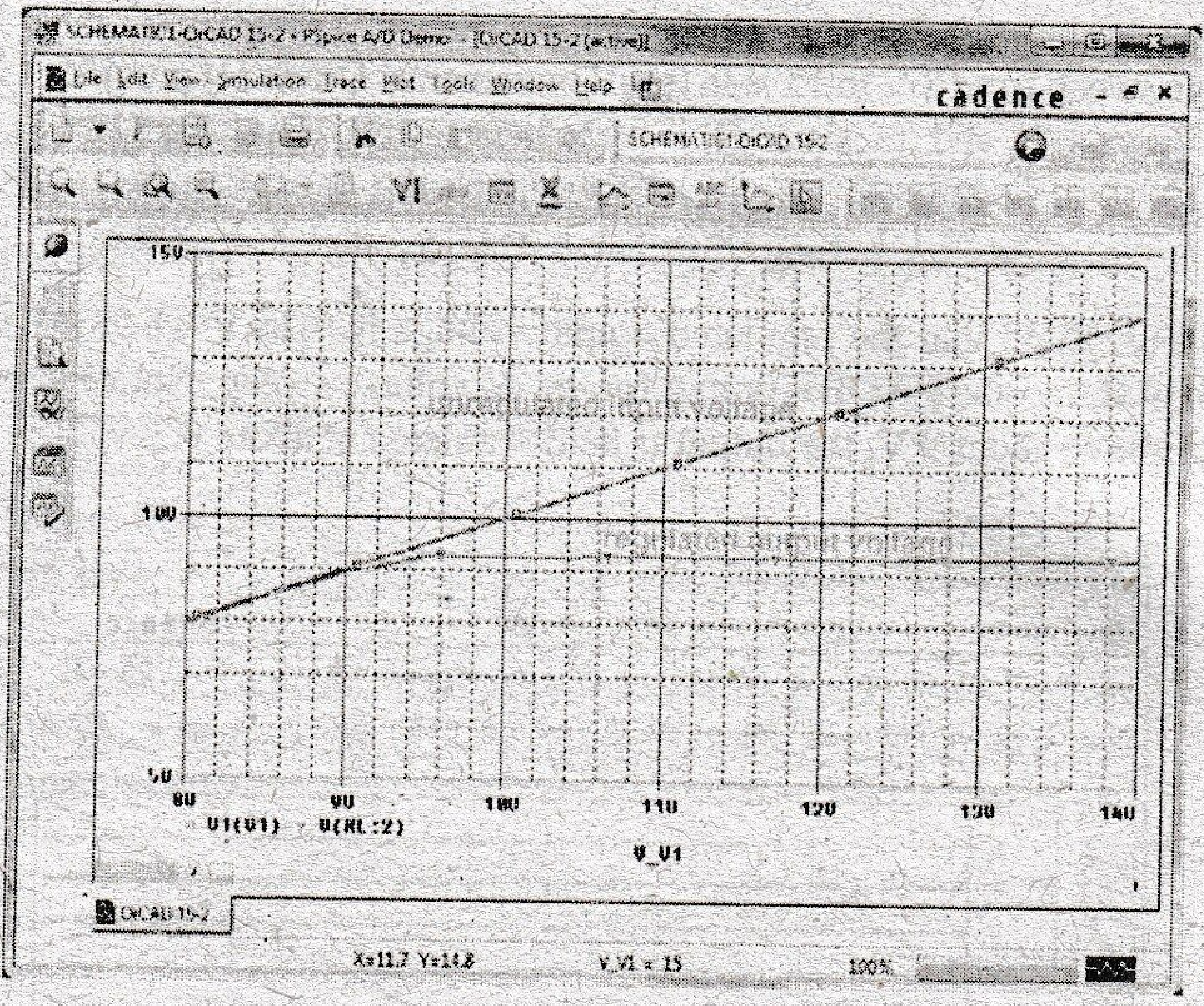


FIG. 15.41
Probe output for the dc voltage sweep of Fig. 15.40.

PROBLEMS

**Note:* Asterisks indicate more difficult problems.

15.2 General Filter Considerations

1. What is the ripple factor of a sinusoidal signal having peak ripple of 2 V on an average of 50 V?
2. A filter circuit provides an output of 28 V unloaded and 25 V under full-load operation. Calculate the percentage voltage regulation.
3. A half-wave rectifier develops 20 V dc. What is the value of the ripple voltage?
4. What is the rms ripple voltage of a full-wave rectifier with output voltage 8 V dc?

15.3 Capacitor Filter

5. A simple capacitor filter fed by a full-wave rectifier develops 14.5 V dc at 8.5% ripple factor. What is the output ripple voltage (rms)?
6. A full-wave rectified signal of 18 V peak is fed into a capacitor filter. What is the voltage regulation of the filter if the output is 17 V dc at full load?
7. A full-wave rectified voltage of 18 V peak is connected to a 400-μF filter capacitor. What are the ripple and dc voltages across the capacitor at a load of 100 mA?
8. A full-wave rectifier operating from the 60-Hz ac supply produces a 20-V peak rectified voltage. If a 200-μF capacitor is used, calculate the ripple at a load of 120 mA.
9. A full-wave rectifier (operating from a 60-Hz supply) drives a capacitor-filter circuit ($C = 100\ \mu$F), which develops 12 V dc when connected to a 2.5-kΩ load. Calculate the output voltage ripple.
10. Calculate the size of the filter capacitor needed to obtain a filtered voltage having 15% ripple at a load of 150 mA. The full-wave rectified voltage is 24 V dc, and the supply is 60 Hz.

*11. A 500-μF capacitor provides a load current of 200 mA at 8% ripple. Calculate the peak rectified voltage obtained from the 60-Hz supply and the dc voltage across the filter capacitor.

12. Calculate the size of the filter capacitor needed to obtain a filtered voltage with 7% ripple at a load of 200 mA. The full-wave rectified voltage is 30 V dc and the supply is 60 Hz.
13. Calculate the percentage ripple for the voltage developed across a 120-μF filter capacitor when providing a load current of 80 mA. The full-wave rectifier operating from the 60-Hz supply develops a peak rectified voltage of 25 V.

15.4 *RC* Filter

14. An *RC* filter stage is added after a capacitor filter to reduce the percentage of ripple to 2%. Calculate the ripple voltage at the output of the *RC* filter stage providing 80 V dc.

***15.** An *RC* filter stage ($R = 33\ \Omega$, $C = 120\ \mu F$) is used to filter a signal of 24 V dc with 2 V rms operating from a full-wave rectifier. Calculate the percentage ripple at the output of the *RC* section for a 100-mA load. Also calculate the ripple of the filtered signal applied to the *RC* stage.

***16.** A simple capacitor filter has an input of 40 V dc. If this voltage is fed through an *RC* filter section ($R = 50\ \Omega$, $C = 40\ \mu F$), what is the load current for a load resistance of 500 Ω?

17. Calculate the rms ripple voltage at the output of an *RC* filter section that feeds a 1-kΩ load when the filter input is 50 V dc with 2.5-V rms ripple from a full-wave rectifier and capacitor filter. The *RC* filter section components are $R = 100\ \Omega$ and $C = 100\ \mu F$.

18. If the no-load output voltage for Problem 17 is 50 V, calculate the percentage voltage regulation with a 1-kΩ load.

15.5 Discrete Transistor Voltage Regulation

***19.** Calculate the output voltage and Zener diode current in the regulator circuit of Fig. 15.42.

20. What regulated output voltage results in the circuit of Fig. 15.43?

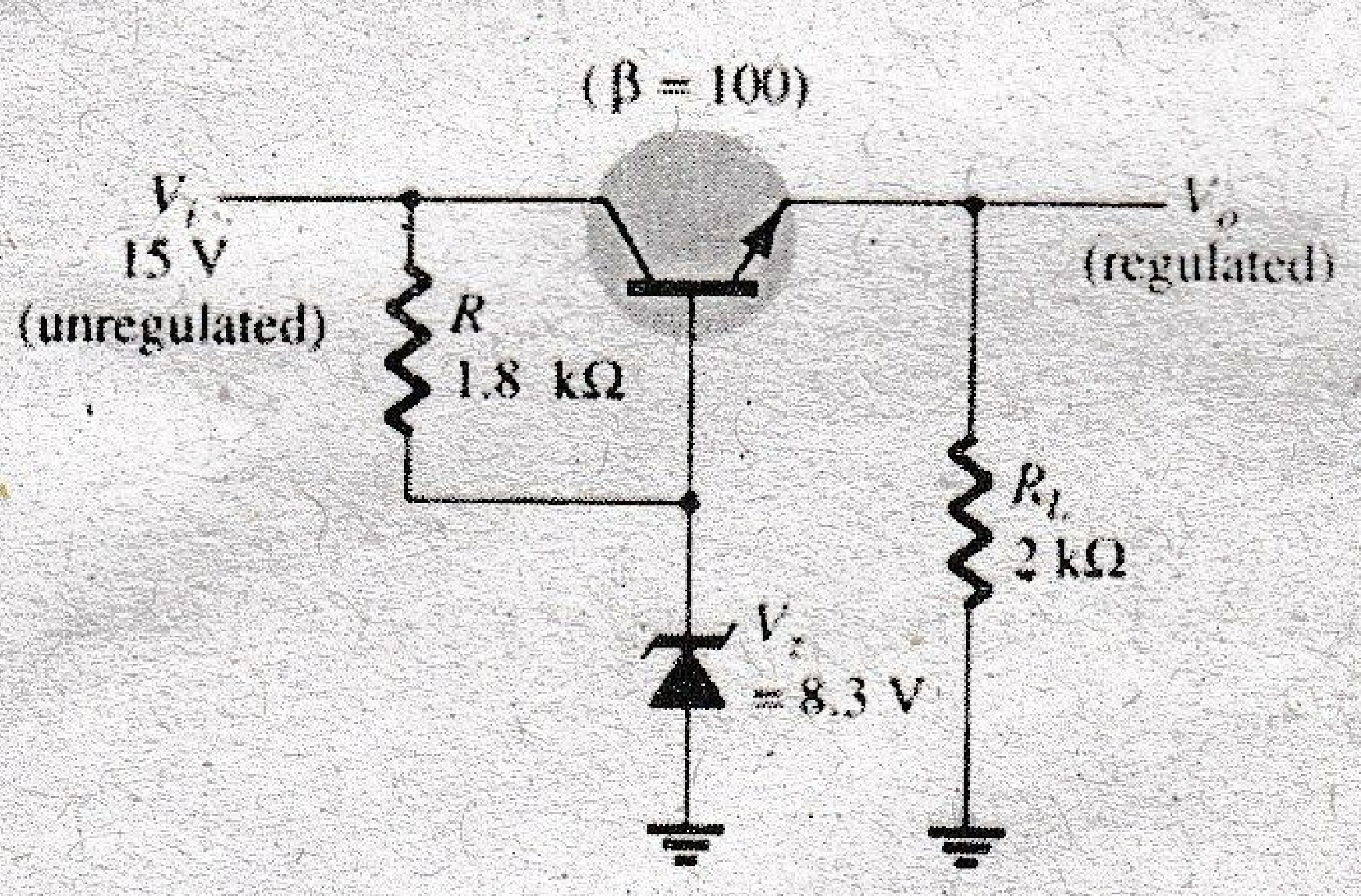


FIG. 15.42
Problem 19.

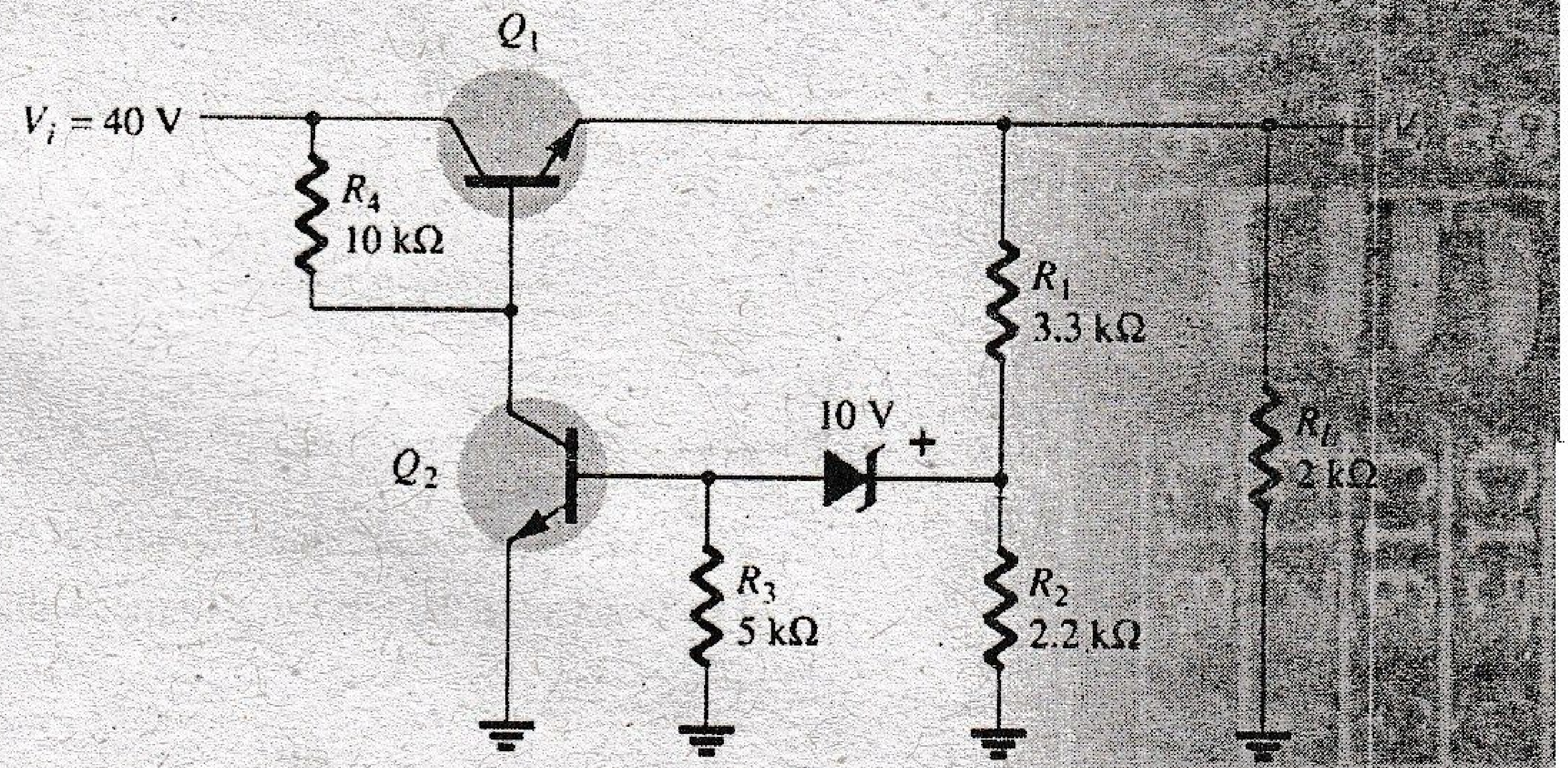


FIG. 15.43
Problem 20.

21. Calculate the regulated output voltage in the circuit of Fig. 15.44.

22. Determine the regulated voltage and circuit currents for the shunt regulator of Fig. 15.45.

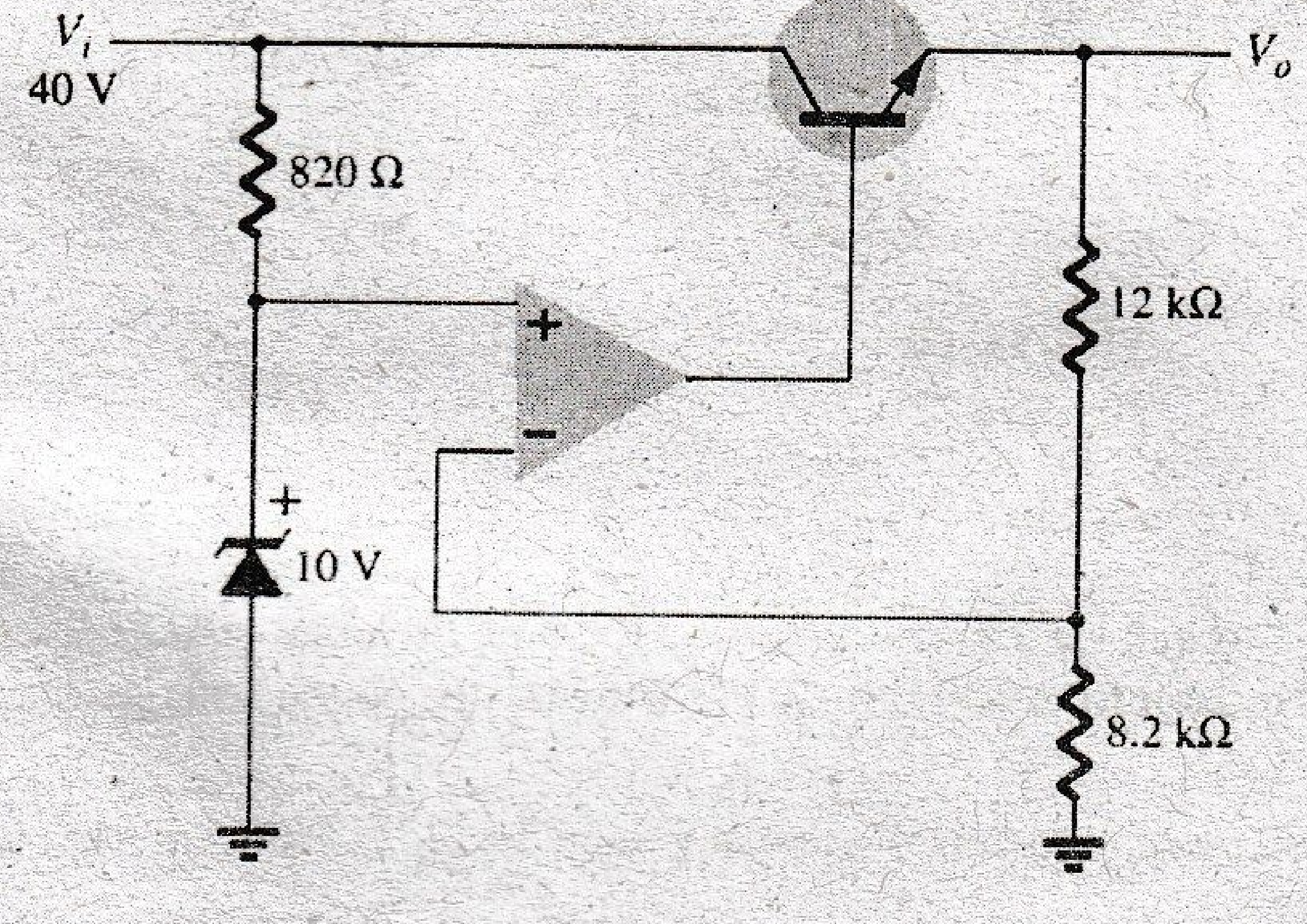


FIG. 15.44
Problem 21.

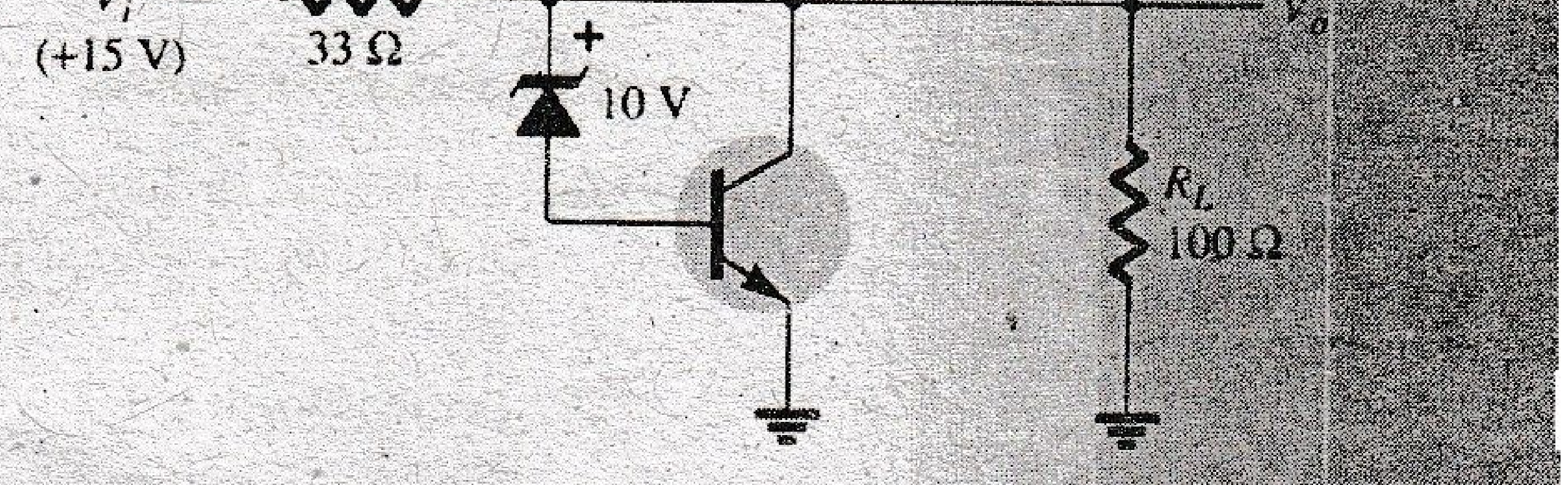


FIG. 15.45
Problem 22.

15.6 IC Voltage Regulators

23. Draw the circuit of a voltage supply comprised of a full-wave bridge rectifier, capacitor filter, and IC regulator to provide an output of +12 V.

***24.** Calculate the minimum input voltage of the full-wave rectifier and filter capacitor network in Fig. 15.46 when connected to a load drawing 250 mA.

***25.** Determine the maximum value of load current at which regulation is maintained for the circuit of Fig. 15.47.

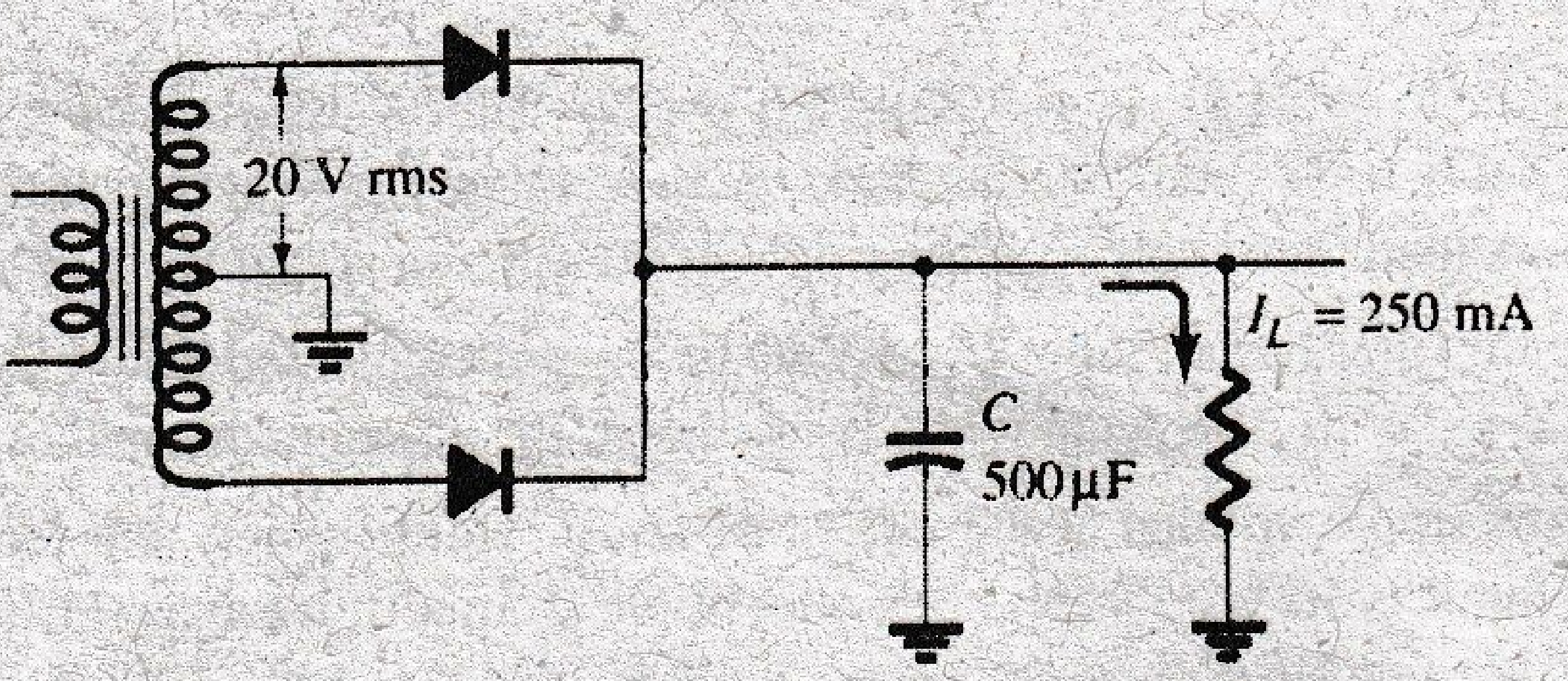


FIG. 15.46
Problem 24.

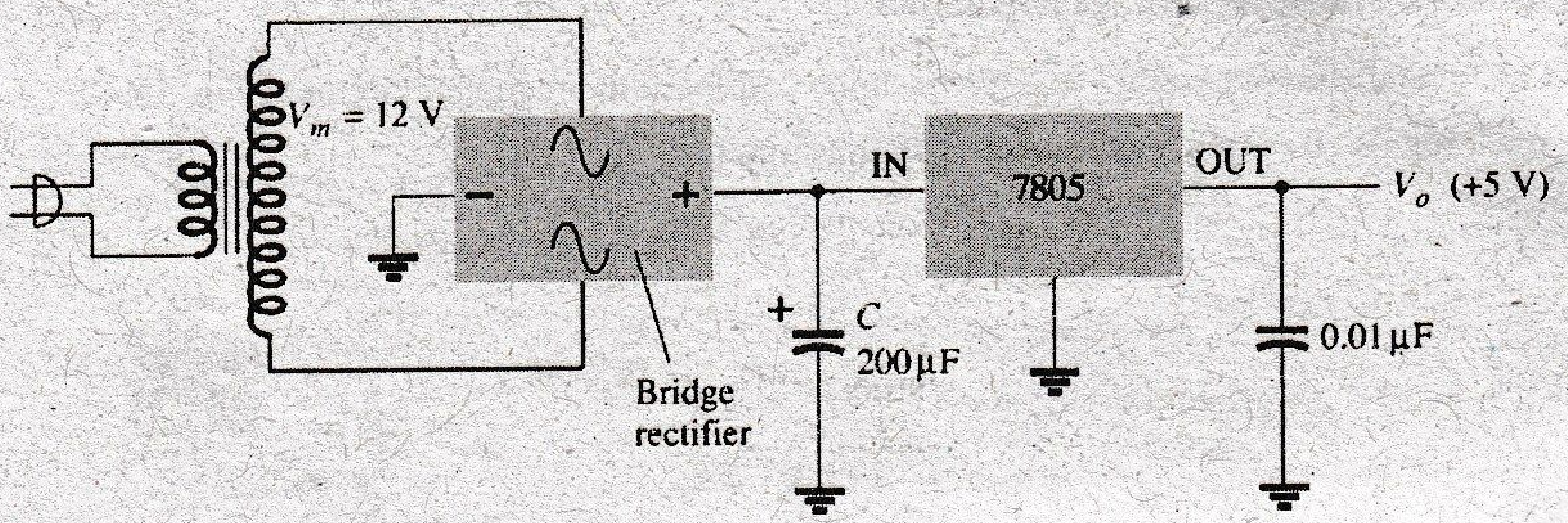


FIG. 15.47
Problem 25.

26. Determine the regulated voltage in the circuit of Fig. 15.30 with R_1 = 240 Ω and R_2 = 1.8 kΩ.

27. Determine the regulated output voltage from the circuit of Fig. 15.48.

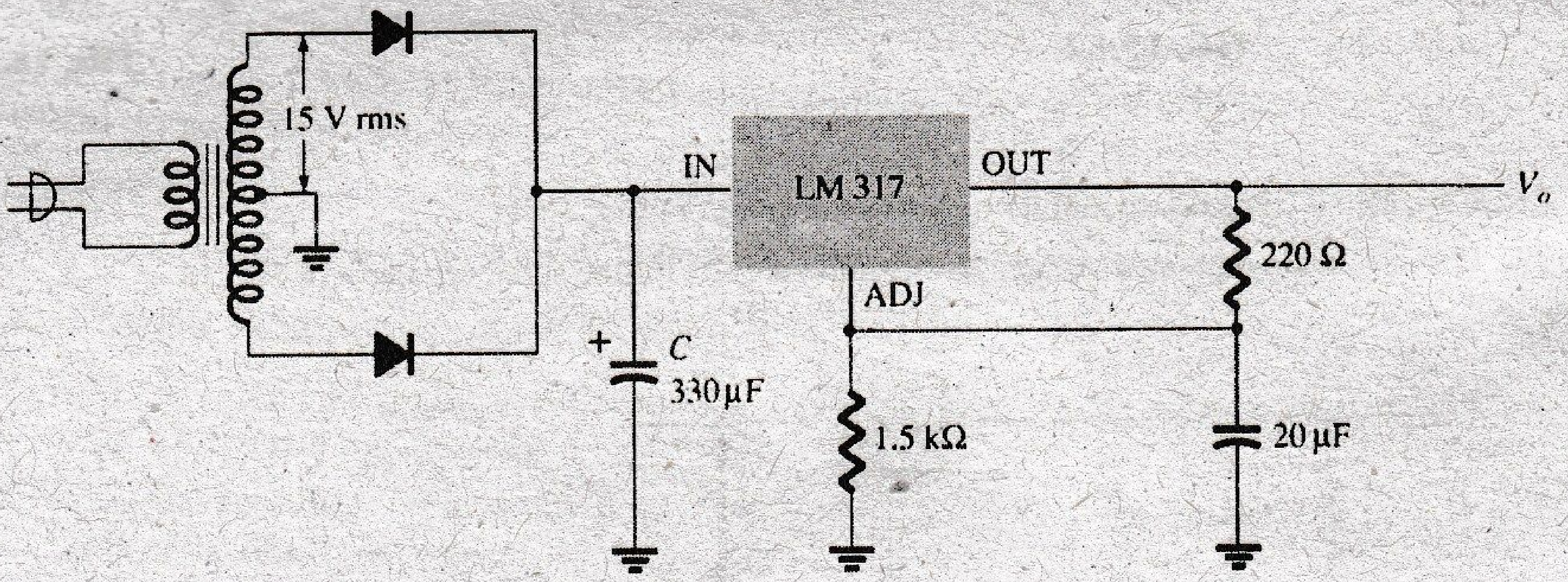


FIG. 15.48
Problem 27.

15.9 Computer Analysis

***28.** Modify the circuit of Fig. 15.38 to include a load resistor R_L. Keeping the input voltage fixed at 10 V, do a sweep of the load resistor from 100 Ω to 20 kΩ, showing the output voltage using Probe.

***29.** For the circuit of Fig. 15.40, do a sweep showing the output voltage for R_L varied from 5 kΩ to 20 kΩ.

***30.** Run a PSpice analysis of the circuit of Fig. 15.19 for V_Z = 4.7 V and beta (Q_1) = beta (Q_2) = 100, and vary V_i from 5 V to 20 V.