(c) For this design, use the diode exponential model to determine the actual change in V_O when a current $I_L = 1$ mA is drawn from the regulator.

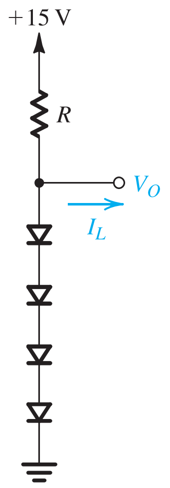

Figure E4.15

Ans. (a) $R = 2.4\ \text{k}\Omega$; (b) $I_S = 4.7 \times 10^{-16}$ A; (c) –23 mV

4.4 Operation in the Reverse Breakdown Region—Zener Diodes

The very steep i–v curve that the diode exhibits in the breakdown region (Fig. 4.8) and the almost-constant voltage drop that this indicates suggest that diodes operating in the breakdown region can be used in the design of voltage regulators. From the previous section, the reader will recall that voltage regulators are circuits that provide a constant dc output voltage in the face of changes in their load current and in the system power-supply voltage. This in fact turns out to be an important application of diodes operating in the reverse breakdown region, and special diodes are manufactured to operate specifically in the breakdown region. Such diodes are called **breakdown diodes** or, more commonly, as noted earlier, **zener diodes**.

Figure 4.18 shows the circuit symbol of the zener diode. In normal applications of zener diodes, current flows into the cathode, and the cathode is positive with respect to the anode. Thus I_Z and V_Z in Fig. 4.18 have positive values.

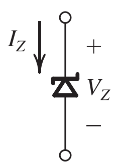

Figure 4.18 Circuit symbol for a zener diode.

4.4.1 Specifying and Modeling the Zener Diode

Figure 4.19 shows details of the diode i–v characteristic in the breakdown region. We observe that for currents greater than the **knee current** I_{ZK} (specified on the data sheet of the zener diode), the i–v characteristic is almost a straight line. The manufacturer usually specifies the voltage across the zener diode V_Z at a specified test current, I_{ZT}. We have indicated these parameters in Fig. 4.19 as the coordinates of the point labeled Q. Thus a 6.8-V zener diode will exhibit a 6.8-V drop at a specified test current of, say, 10 mA. As the current through the zener deviates from I_{ZT}, the voltage across it will change, though only slightly. Figure 4.19 shows that corresponding to current change ΔI the zener voltage changes by ΔV, which is related to ΔI by

$$\Delta V = r_z \Delta I$$

where r_z is the inverse of the slope of the almost-linear i–v curve at point Q. Resistance r_z is the **incremental resistance** of the zener diode at operating point Q. It is also known as the **dynamic resistance** of the zener, and its value is specified on the device data sheet. Typically, r_z is in the range of a few ohms to a few tens of ohms. Obviously, the lower the value of r_z is, the more constant the zener voltage remains as its current varies, and thus the more ideal its performance becomes in the design of voltage regulators. In this regard, we observe from Fig. 4.19 that while r_z remains low and almost constant over a wide range of current, its value increases considerably in the vicinity of the knee. Therefore, as a general design guideline, one should avoid operating the zener in this low-current region.

Zener diodes are fabricated with voltages V_Z in the range of a few volts to a few hundred volts. In addition to specifying V_Z (at a particular current I_{ZT}), r_z, and I_{ZK}, the manufacturer

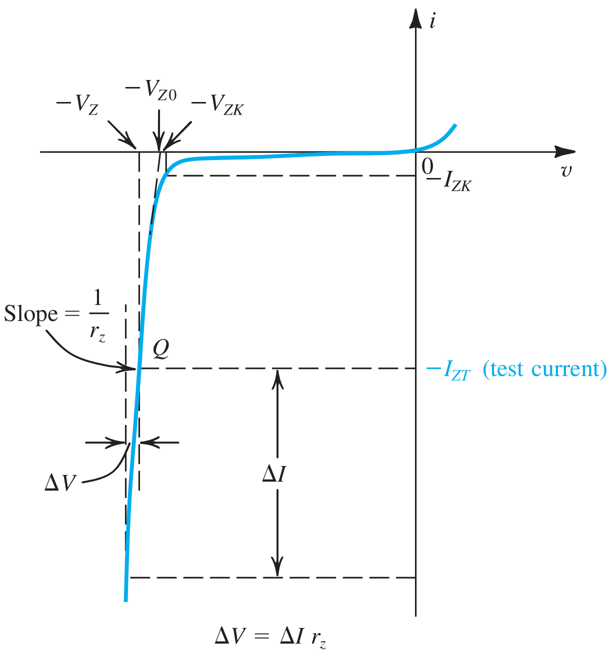

Figure 4.19 The diode i–v characteristic with the breakdown region shown in some detail.

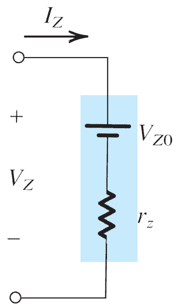

Figure 4.20 Model for the zener diode.

also specifies the maximum power that the device can safely dissipate. Thus a 0.5-W, 6.8-V zener diode can operate safely at currents up to a maximum of about 70 mA.

The almost-linear i–v characteristic of the zener diode suggests that the device can be modeled as indicated in Fig. 4.20. Here V_{Z0} denotes the point at which the straight line of slope $1/r_z$ intersects the voltage axis (refer to Fig. 4.19). Although V_{Z0} is shown in Fig. 4.19 to be slightly different from the knee voltage V_{ZK}, in practice their values are almost equal. The equivalent circuit model of Fig. 4.20 can be analytically described by

$$V_Z = V_{Z0} + r_z I_Z \tag{4.20}$$

and it applies for $I_Z > I_{ZK}$ and, obviously, $V_Z > V_{Z0}$.

4.4.2 Use of the Zener as a Shunt Regulator

We now illustrate, by way of an example, the use of zener diodes in the design of shunt regulators, so named because the regulator circuit appears in parallel (shunt) with the load.

Example 4.7

The 6.8-V zener diode in the circuit of Fig. 4.21(a) is specified to have $V_Z = 6.8$ V at $I_Z = 5$ mA, $r_z = 20\ \Omega$, and $I_{ZK} = 0.2$ mA. The supply voltage V^+ is nominally 10 V but can vary by ± 1 V.

(a) Find V_O with no load and with V^+ at its nominal value.
(b) Find the change in V_O resulting from the ± 1-V change in V^+. Note that $(\Delta V_O/\Delta V^+)$, usually expressed in mV/V, is known as **line regulation**.
(c) Find the change in V_O resulting from connecting a load resistance R_L that draws a current $I_L = 1$ mA, and hence find the **load regulation** $(\Delta V_O/\Delta I_L)$ in mV/mA.
(d) Find the change in V_O when $R_L = 2$ kΩ.
(e) Find the value of V_O when $R_L = 0.5$ kΩ.
(f) What is the minimum value of R_L for which the diode still operates in the breakdown region?

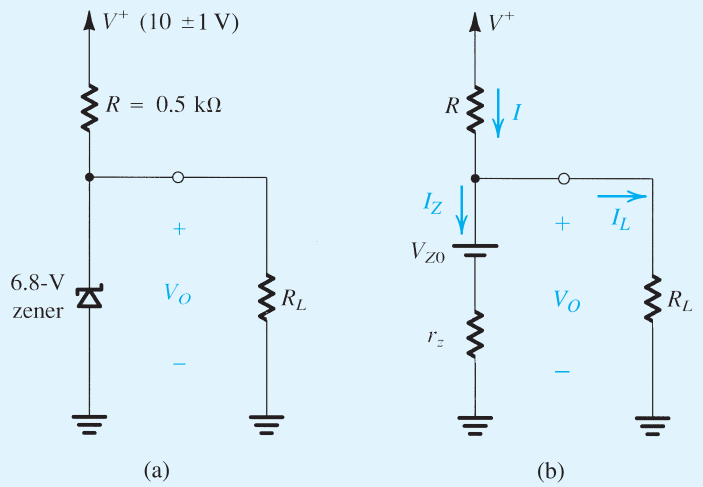

Figure 4.21 **(a)** Circuit for Example 4.7. **(b)** The circuit with the zener diode replaced with its equivalent circuit model.

Solution

First we must determine the value of the parameter V_{Z0} of the zener diode model. Substituting $V_Z = 6.8$ V, $I_Z = 5$ mA, and $r_z = 20\ \Omega$ in Eq. (4.20) yields $V_{Z0} = 6.7$ V. Figure 4.21(b) shows the circuit with the zener diode replaced with its model.

(a) With no load connected, the current through the zener is given by

$$I_Z = I = \frac{V^+ - V_{Z0}}{R + r_z}$$

$$= \frac{10 - 6.7}{0.5 + 0.02} = 6.35 \text{ mA}$$

Thus,

$$V_O = V_{Z0} + I_Z r_z$$

$$= 6.7 + 6.35 \times 0.02 = 6.83 \text{ V}$$

(b) For a ±1-V change in V^+, the change in output voltage can be found from

$$\Delta V_O = \Delta V^+ \frac{r_z}{R + r_z}$$

$$= \pm 1 \times \frac{20}{500 + 20} = \pm 38.5 \text{ mV}$$

Thus,

$$\text{Line regulation} = 38.5 \text{ mV/V}$$

Example 4.7 *continued*

(c) When a load resistance R_L that draws a load current $I_L = 1$ mA is connected, the zener current will decrease by 1 mA. The corresponding change in zener voltage can be found from

$$\Delta V_O = r_z \Delta I_Z$$
$$= 20 \times -1 = -20 \text{ mV}$$

Thus the load regulation is

$$\text{Load regulation} \equiv \frac{\Delta V_O}{\Delta I_L} = -20 \text{ mV/mA}$$

(d) When a load resistance of 2 kΩ is connected, the load current will be approximately 6.8 V/2 kΩ = 3.4 mA. Thus the change in zener current will be $\Delta I_Z = -3.4$ mA, and the corresponding change in zener voltage (output voltage) will thus be

$$\Delta V_O = r_z \Delta I_Z$$
$$= 20 \times -3.4 = -68 \text{ mV}$$

This value could have been obtained by multiplying the load regulation by the value of I_L (3.4 mA).
(e) An R_L of 0.5 kΩ would draw a load current of 6.8/0.5 = 13.6 mA. This is not possible, because the current I supplied through R is only 6.4 mA (for $V^+ = 10$ V). Therefore, the zener must be cut off. If this is indeed the case, then V_O is determined by the voltage divider formed by R_L and R (Fig. 4.21a),

$$V_O = V^+ \frac{R_L}{R + R_L}$$
$$= 10 \frac{0.5}{0.5 + 0.5} = 5 \text{ V}$$

Since this voltage is lower than the breakdown voltage of the zener, the diode is indeed no longer operating in the breakdown region.
(f) For the zener to be at the edge of the breakdown region, $I_Z = I_{ZK} = 0.2$ mA and $V_Z \simeq V_{ZK} \simeq 6.7$ V. At this point the lowest (worst-case) current supplied through R is $(9 - 6.7)/0.5 = 4.6$ mA, and thus the load current is $4.6 - 0.2 = 4.4$ mA. The corresponding value of R_L is

$$R_L = \frac{6.7}{4.4} \simeq 1.5 \text{ k}\Omega$$

4.4.3 Temperature Effects

The dependence of the zener voltage V_Z on temperature is specified in terms of its **temperature coefficient TC**, or **temco** as it is commonly known, which is usually expressed in mV/°C. The value of TC depends on the zener voltage, and for a given diode the TC varies with the operating current. Zener diodes whose V_Z are lower than about 5 V exhibit a negative TC. On the other hand, zeners with higher voltages exhibit a positive TC. The TC of a zener diode with a V_Z of about 5 V can be made zero by operating the diode at a specified current. Another commonly used technique for obtaining a reference voltage with low temperature coefficient