

5-2 The Loaded Zener Regulator

Figure 5-5a shows a *loaded* zener regulator, and Fig. 5-5b shows the same circuit with grounds. The zener diode operates in the breakdown region and holds the load voltage constant. Even if the source voltage changes or the load resistance varies, the load voltage will remain fixed and equal to the zener voltage.

Breakdown Operation

How can you tell whether the zener diode of Fig. 5-5 is operating in the breakdown region? Because of the voltage divider, the Thevenin voltage facing the diode is:

$$V_{TH} = \frac{R_L}{R_S + R_L} V_S \quad (5-2)$$

This is the voltage that exists when the zener diode is disconnected from the circuit. This Thevenin voltage has to be greater than the zener voltage; otherwise, breakdown cannot occur.

Series Current

Unless otherwise indicated, in all subsequent discussions we assume that the zener diode is operating in the breakdown region. In Fig. 5-5, the current through the series resistor is given by:

$$I_S = \frac{V_S - V_Z}{R_S} \quad (5-3)$$

This is Ohm's law applied to the current-limiting resistor. It is the same whether or not there is a load resistor. In other words, if you disconnect the load resistor, the current through the series resistor still equals the voltage across the resistor divided by the resistance.

Load Current

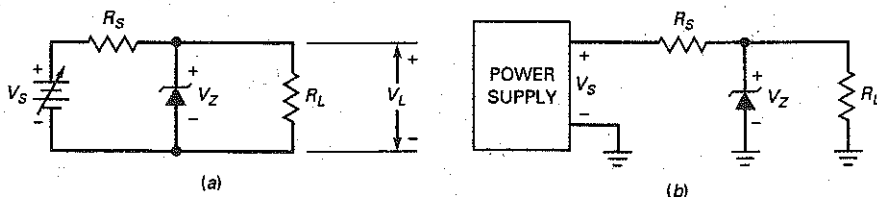
Ideally, the load voltage equals the zener voltage because the load resistor is in parallel with the zener diode. As an equation:

$$V_L = V_Z \quad (5-4)$$

This allows us to use Ohm's law to calculate the load current:

$$I_L = \frac{V_L}{R_L} \quad (5-5)$$

Figure 5-5 Loaded zener regulator. (a) Basic circuit; (b) practical circuit.



Zener Current

With Kirchhoff's current law:

$$I_S = I_Z + I_L$$

The zener diode and the load resistor are in parallel. The sum of their currents has to equal the total current, which is the same as the current through the series resistor.

We can rearrange the foregoing equation to get this important formula:

$$I_Z = I_S - I_L \quad (5-6)$$

This tells you that the zener current no longer equals the series current, as it does in an unloaded zener regulator. Because of the load resistor, the zener current now equals the series current minus the load current.

Table 5-1 summarizes the steps in the analysis of a loaded zener regulator. You start with the series current, followed by the load voltage and load current, and finally the zener current.

Zener Effect

When the breakdown voltage is greater than 6 V, the cause of the breakdown is the avalanche effect, discussed in Chap. 2. The basic idea is that minority carriers are accelerated to high enough speeds to dislodge other minority carriers, producing a chain or avalanche effect that results in a large reverse current.

The zener effect is different. When a diode is heavily doped, the depletion layer becomes very narrow. Because of this, the electric field across the depletion layer (voltage divided by distance) is very intense. When the field strength reaches approximately 300,000 V/cm, the field is intense enough to pull electrons out of their valence orbits. The creation of free electrons in this way is called the zener effect (also known as *high-field emission*). This is distinctly different from the avalanche effect, which depends on high-speed minority carriers dislodging valence electrons.

When the breakdown voltage is less than 4 V, only the zener effect occurs. When the breakdown voltage is greater than 6 V, only the avalanche effect occurs. When the breakdown voltage is between 4 and 6 V, both effects are present.

The zener effect was discovered before the avalanche effect, so all diodes used in the breakdown region came to be known as zener diodes. Although you may occasionally hear the term *avalanche diode*, the name *zener diode* is in general use for all breakdown diodes.

Table 5-1 Analyzing a Loaded Zener Regulator

	Process	Comment
Step 1	Calculate the series current, Eq. (5-3)	Apply Ohm's law to R_S
Step 2	Calculate the load voltage, Eq. (5-4)	Load voltage equals diode voltage
Step 3	Calculate the load current, Eq. (5-5)	Apply Ohm's law to R_L
Step 4	Calculate the zener current, Eq. (5-6)	Apply the current law to the diode

GOOD TO KNOW

For zener voltages between approximately 3 and 8 V, the temperature coefficient is also strongly affected by the reverse current in the diode. The temperature coefficient becomes more positive as current increases.

Temperature Coefficients

GOOD TO KNOW

In applications requiring a highly stable reference voltage, a zener diode is connected in series with one or more semiconductor diodes whose voltage drops change with temperature in the opposite direction that V_Z changes. The result is that V_Z remains very stable even though the temperature may vary over a wide range.

When the ambient temperature changes, the zener voltage will change slightly. On data sheets the effect of temperature is listed under the **temperature coefficient**, which is defined as the change in breakdown voltage per degree of increase. The temperature coefficient is negative for breakdown voltages less than 4 V (zener effect). For instance, a zener diode with a breakdown voltage of 3.9 V may have a temperature coefficient of $-1.4 \text{ mV}/^\circ\text{C}$. If temperature increases by 1° , the breakdown voltage decreases by 1.4 mV.

On the other hand, the temperature coefficient is positive for breakdown voltages greater than 6 V (avalanche effect). For instance, a zener diode with a breakdown voltage of 6.2 V may have a temperature coefficient of $2 \text{ mV}/^\circ\text{C}$. If the temperature increases by 1° , the breakdown voltage increases by 2 mV.

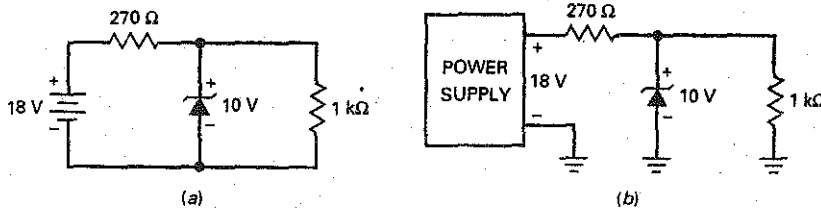
Between 4 and 6 V, the temperature coefficient changes from negative to positive. In other words, there are zener diodes with breakdown voltages between 4 and 6 V in which the *temperature coefficient equals zero*. This is important in some applications when a solid zener voltage is needed over a large temperature range.

Example 5-2

III Multisim

Is the zener diode of Fig. 5-6a operating in the breakdown region?

Figure 5-6 Example.



SOLUTION With Eq. (5-2):

$$V_{TH} = \frac{1 \text{ k}\Omega}{270 \Omega + 1 \text{ k}\Omega} (18 \text{ V}) = 14.2 \text{ V}$$

Since this Thevenin voltage is greater than the zener voltage, the zener diode is operating in the breakdown region.

Example 5-3

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What does the zener current equal in Fig. 5-6b?

SOLUTION You are given the voltage on both ends of the series resistor. Subtract the voltages, and you can see that 8 V is across the series resistor. Then Ohm's law gives:

$$I_S = \frac{8 \text{ V}}{270 \Omega} = 29.6 \text{ mA}$$

Since the load voltage is 10 V, the load current is:

$$I_L = \frac{10 \text{ V}}{1 \text{ k}\Omega} = 10 \text{ mA}$$

The zener current is the difference between the two currents:

$$I_Z = 29.6 \text{ mA} - 10 \text{ mA} = 19.6 \text{ mA}$$

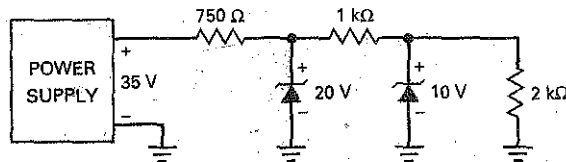
PRACTICE PROBLEM 5-3 Using Fig. 5-6b, change the power supply to 15 V and calculate I_S , I_L , and I_Z .

Example 5-4

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What does the circuit of Fig. 5-7 do?

Figure 5-7 Example.



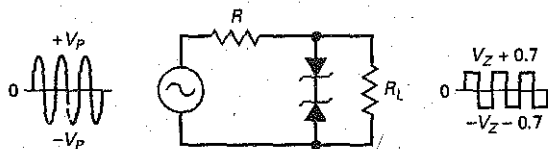
SOLUTION This is an example of a **preregulator** (the first zener diode) driving a zener regulator (the second zener diode). First, notice that the preregulator has an output voltage of 20 V. This is the input to the second zener regulator, whose output is 10 V. The basic idea is to provide the second regulator with a well-regulated input, so that the final output is extremely well regulated.

Example 5-5

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What does the circuit of Fig. 5-8 do?

Figure 5-8 Zener diodes used for waveshaping.



SOLUTION In most applications, zener diodes are used in voltage regulators where they remain in the breakdown region. But there are exceptions. Sometimes zener diodes are used in waveshaping circuits like Fig. 5-8.

Notice the back-to-back connection of two zener diodes. On the positive half cycle, the upper diode conducts and the lower diode breaks down. Therefore, the output is clipped as shown. The clipping level equals the zener voltage (broken-down diode) plus 0.7 V (forward-biased diode).

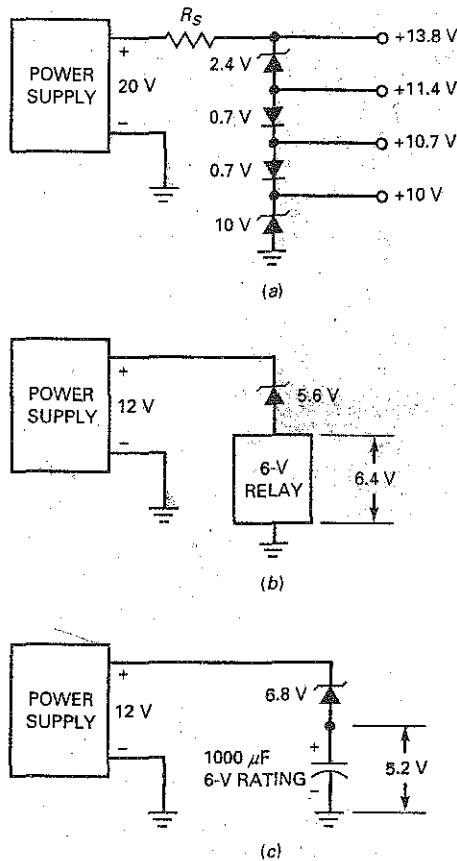
On the negative half cycle, the action is reversed. The lower diode conducts, and the upper diode breaks down. In this way, the output is almost a square wave. The larger the input sine wave, the better-looking the output square wave.

PRACTICE PROBLEM 5-5 In Fig. 5-8, the V_Z for each diode is 3.3 V. What would the voltage across R_L be?

Example 5-6

Briefly describe the circuit action for each of the circuits in Fig. 5-9.

Figure 5-9 Zener applications. (a) Producing nonstandard output voltages; (b) using a 6-V relay in a 12-V system; (c) using a 6-V capacitor in a 12-V system.



SOLUTION Figure 5-9a shows how zener diodes and ordinary silicon diodes can produce several dc output voltages, given a 20-V power supply. The bottom diode produces an output of 10 V. Each silicon diode is forward biased, producing outputs of 10.7 V and 11.4 V, as shown. The top diode has a breakdown voltage of 2.4 V, giving an output of 13.8 V. With other combinations of zener and silicon diodes, a circuit like this can produce different dc output voltages.

If you try to connect a 6-V relay to a 12-V system, you will probably damage the relay. It is necessary to drop some of the voltage. Figure 5-9b shows one way to do this. By connecting a 5.6-V zener diode in series with the relay, only 6.4 V appears across the relay, which is usually within the tolerance of the relay's voltage rating.

Large electrolytic capacitors often have small voltage ratings. For instance, an electrolytic capacitor of 1000 μF may have a voltage rating of only 6 V. This means that the maximum voltage across the capacitor should be less than 6 V. Figure 5-9c shows a workaround solution in which a 6-V electrolytic capacitor is used with a 12-V power supply. Again, the idea is to use a zener diode to drop some of the voltage. In this case, the zener diode drops 6.8 V, leaving only 5.2 V across the capacitor. This way, the electrolytic capacitor can filter the power supply and still remain with its voltage rating.