Chapter 3: Zener Diodes Circuits

The Zener model to be employed for the “on” state will be as shown in Figure a. For the “off” state as defined by a voltage less than V_Z but greater than 0 V with the polarity indicated in Figure 3.1-b, the Zener equivalent is the open circuit that appears in the same figure

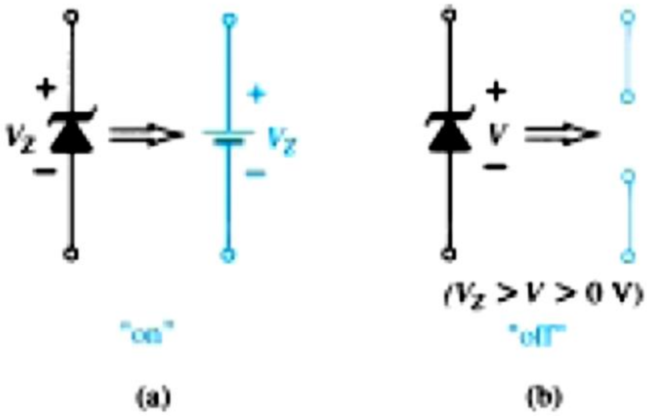


Figure 3.1 : Zener diode equivalents for the (a) “on” and (b) “off” states.

The simplest Zener diode circuit appears in Figure 3.2.

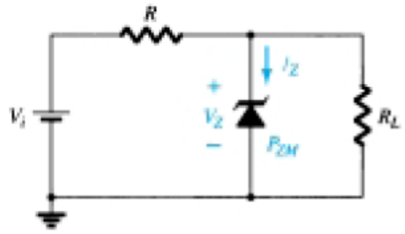
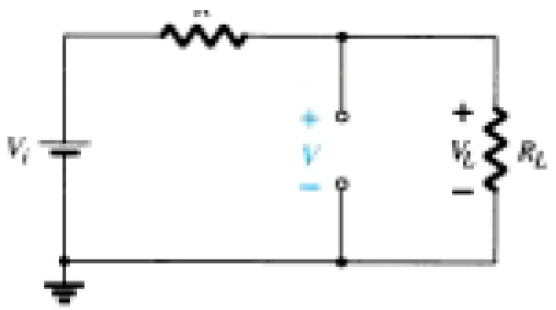


Figure 3.2: Basic Zener diode regulator.

3.1 Fixed V_i and R_L

The analysis can fundamentally be broken down into two steps:

1. Determine the state of the Zener diode by removing it from the network and calculating the voltage across the resulting open circuit, as shown below:



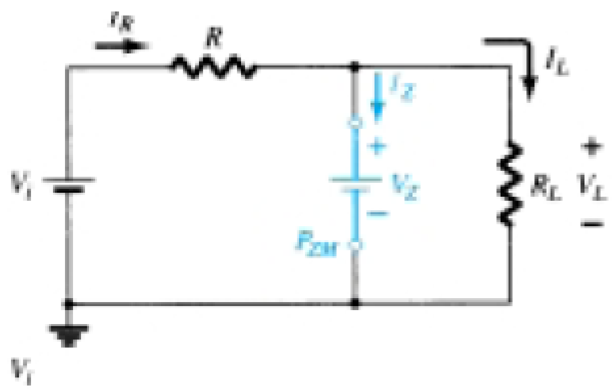
Using voltage divider rule:

$$V = V_L = \frac{R_L V_i}{R + R_L}$$

- If $V >= VZ$, the Zener diode is "on" and the equivalent model of Figure a can be substituted.
- If $V < VZ$, the diode is "off" and the open-circuit equivalence of Figure b is substituted.

2. Substitute the appropriate equivalent circuit (Figure a or b) and solve for the desired unknowns.

- If the diode is ON:



Then

$$V_L = V_Z$$

Apply KCL to find I_Z:

$$I_R = I_Z + I_L$$

$$I_Z = I_R - I_L$$

Where,

$$I_L = \frac{V_L}{R_L} \quad \text{and} \quad I_R = \frac{V_R}{R} = \frac{V_i - V_L}{R}$$

The power dissipated by the Zener diode is determined by

$$P_Z = V_Z I_Z$$

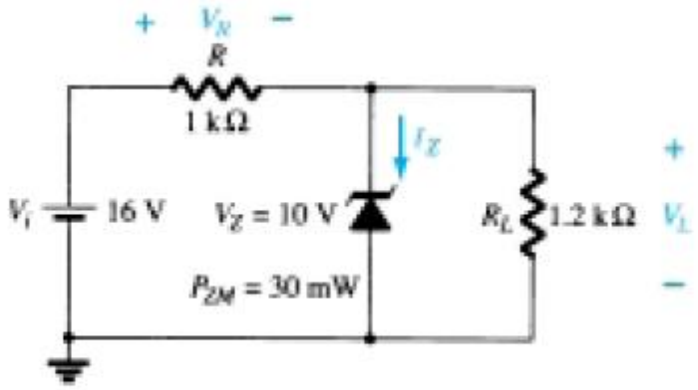
Which must be less than the P_{ZM} *(Maximum Zener Power)* specified for the device.

In summary:

1. Check the Zener diode state.
2. If it is ON, then the regulator is turned ON. The Zener is Turned ON as soon as the voltage across the Zener diode is V_Z
3. It will then "lock in" at this level and never reach the higher level of *V* volts.
4. Zener diodes are most frequently used in regulator networks or as a reference voltage.
5. It maintains a fixed voltage across the load RL. For values of applied voltage greater than required to turn the Zener diode "on," the voltage across the load will be maintained at VZ volts.

Example 1: (a) For the Zener diode network of Figure 3.3, determine *VL*, *VR*, *IZ*, and *PZ*.

(b) Repeat part (a) with *RL* = 3 k Ohm.

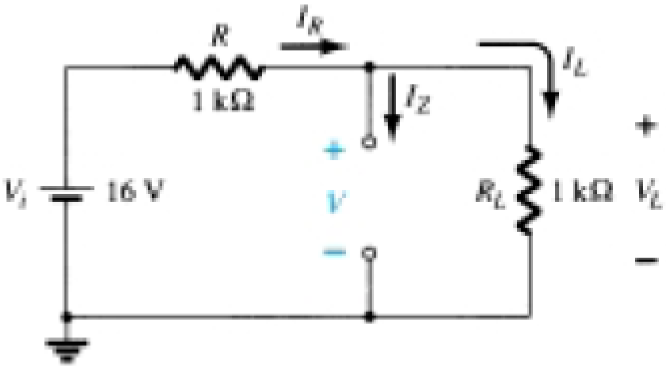


Solution:

Part (a):

$$V = \frac{R_L V_i}{R + R_L} = \frac{1.2\ \text{k}\Omega(16\ \text{V})}{1\ \text{k}\Omega + 1.2\ \text{k}\Omega} = 8.73\ \text{V}$$

Since $V<V_Z$; the diode is OFF and the resultant circuit will be



$V_L = V = \mathbf{8.73\ V}$

$V_R = V_i - V_L = 16\ V - 8.73\ \mathrm{V} = \mathbf{7.27\ V}$

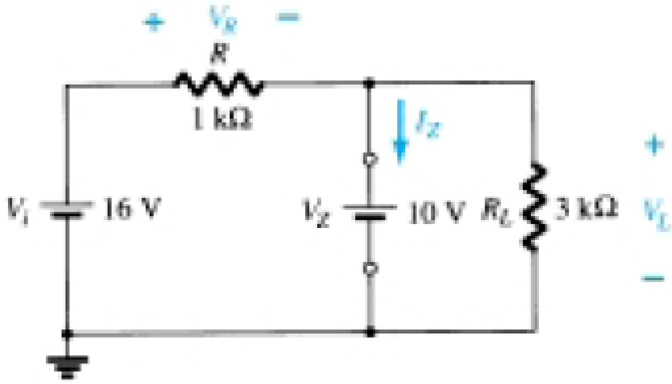
$I_Z = \mathbf{0\ A}$

$P_Z = V_Z I_Z = V_Z(0\ \mathrm{A}) = \mathbf{0\ W}$

Part (b):

$$V = \frac{R_L V_i}{R + R_L} = \frac{3\ \mathrm{k\Omega}(16\ \mathrm{V})}{1\ \mathrm{k\Omega} + 3\ \mathrm{k\Omega}} = 12\ \mathrm{V}$$

Since $V > V_Z$; the diode is ON and the resultant circuit will be



$V_L = V_Z = \mathbf{10\ V}$

$V_R = V_i - V_L = 16\ \mathrm{V} - 10\ \mathrm{V} = \mathbf{6\ V}$

$$I_L = \frac{V_L}{R_L} = \frac{10\ \mathrm{V}}{3\ \mathrm{k\Omega}} = 3.33\ \mathrm{mA}$$

$$\mathrm{I}_R = \frac{V_R}{R} = \frac{6\ \mathrm{V}}{1\ \mathrm{k\Omega}} = 6\ \mathrm{mA}$$

$I_Z = I_R - I_L$ [Eq. (2.18)]

$= 6\ \mathrm{mA} - 3.33\ \mathrm{mA}$

$= \mathbf{2.67\ mA}$

The power dissipated,

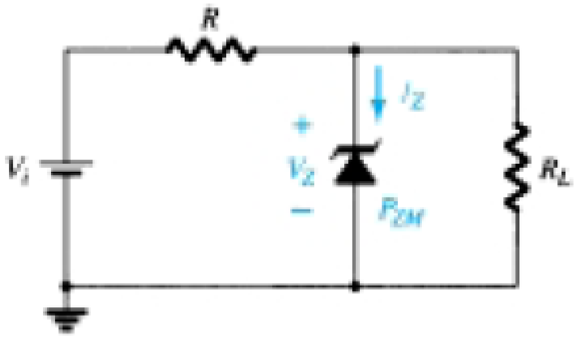
$$P_Z = V_Z I_Z = (10\text{ V})(2.67\text{ mA}) = \mathbf{26.7\ mW}$$

which is less than the specified $P_{ZM} = 30$ mW.

3.2 Fixed Vi, Variable RL

Due to the offset voltage V_Z, there is a specific range of resistor values (and therefore load current) which will ensure that the Zener is in the "on" state. Too small a load resistance R_L will result in a voltage V_L across the load resistor less than V_Z, and the Zener device will be in the "off" state.

To determine the minimum load resistance of the regulator in the figure below that will turn the Zener diode on, simply calculate the value of R_L that will result in a load voltage $V_L = V_Z$. That is:



$$V_L = V_Z = \frac{R_L V_i}{R_L + R}$$

Then the minimum load resistance is :

$$R_{L_{\min}} = \frac{R V_Z}{V_i - V_Z}$$

It means any load resistance greater than R_{Lmin} will make the diode ON.

$$I_{L_{\max}} = \frac{V_L}{R_L} = \frac{V_Z}{R_{L_{\min}}}$$

Once the diode is in the "on" state, the voltage across R remains fixed at

$$V_R = V_i - V_Z$$

and I_R remains fixed at

$$I_R = \frac{V_R}{R}$$

Then the Zener current:

$$I_Z = I_R - I_L$$

Resulting in a minimum I_Z when I_L is a maximum and a maximum I_Z when I_L is a minimum value since I_R is constant.

Since I_Z is limited to I_{ZM} as provided on the data sheet, it does affect the range of R_L and therefore I_L. Substituting I_{ZM} for I_Z establishes the minimum I_L as

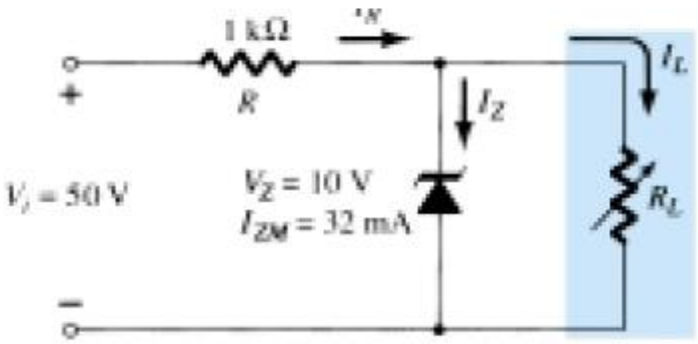
$$I_{L_{min}} = I_R - I_{ZM}$$

and the maximum load resistance as

$$R_{L_{max}} = \frac{V_Z}{I_{L_{min}}}$$

Example: (a) For the circuit shown below, determine the range of R_L and I_L that will result in V_{RL} being maintained at 10 V.

(b) Determine the maximum wattage rating of the diode.



Solution:

(a)

$$R_{L_{\min}} = \frac{RV_Z}{V_i - V_Z} = \frac{(1\ \text{k}\Omega)(10\ \text{V})}{50\ \text{V} - 10\ \text{V}} = \frac{10\ \text{k}\Omega}{40} = \mathbf{250\ \Omega}$$

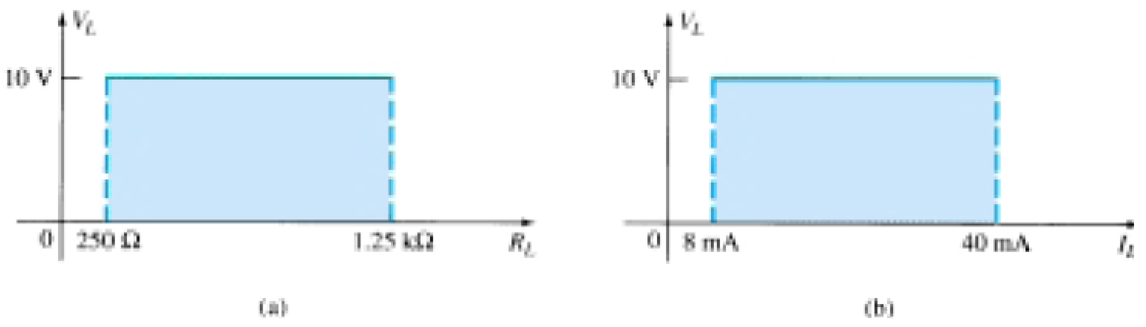
$$V_R = V_i - V_Z = 50\ \text{V} - 10\ \text{V} = \mathbf{40\ V}$$

$$I_R = \frac{V_R}{R} = \frac{40\ \text{V}}{1\ \text{k}\Omega} = \mathbf{40\ mA}$$

$$I_{L_{\min}} = I_R - I_{ZM} = 40\ \text{mA} - 32\ \text{mA} = \mathbf{8\ mA}$$

$$R_{L_{\max}} = \frac{V_Z}{I_{L_{\min}}} = \frac{10\ \text{V}}{8\ \text{mA}} = \mathbf{1.25\ k\Omega}$$

A plot between V_L and R_L and I_L and R_L is shown below:



$$\text{(b)}\ \ P_{\max} = V_Z I_{ZM}$$
$$= (10\ \text{V})(32\ \text{mA}) = \mathbf{320\ mW}$$

3.3 Fixed R_L, Variable V_i

The voltage V_i must be sufficiently large to turn the Zener diode on. The minimum turn-on voltage $V_i = V_{i_{min}}$ is determined by:

$$V_L = V_Z = \frac{R_L V_i}{R_L + R}$$

$$\boxed{V_{i_{\min}} = \frac{(R_L + R)V_Z}{R_L}}$$

The maximum value of V_i is limited by the maximum Zener current I_{ZM}.

Since $I_{ZM} = I_R - I_L$,

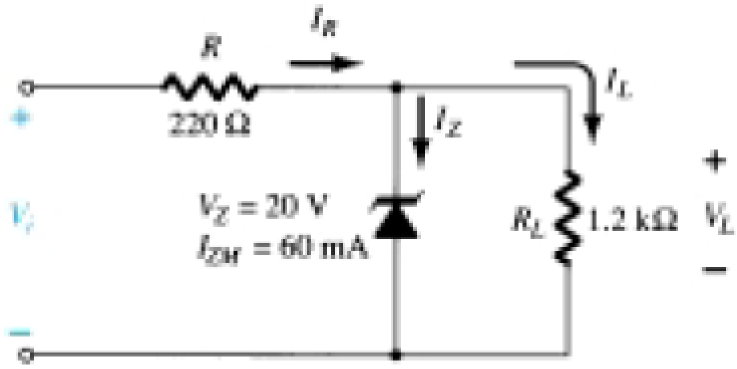
$$I_{R_{max}} = I_{ZM} + I_L$$

Since I_L is fixed at V_Z/R_L and I_{ZM} is the maximum value of I_Z, the maximum V_i is defined by

$$V_{i_{max}} = V_{R_{max}} + V_Z$$

$$V_{i_{max}} = I_{R_{max}} R + V_Z$$

Example: Determine the range of values of V_i that will maintain the Zener diode of the figure below in the "ON" state.



Solution:

$$V_{i_{min}} = \frac{(R_L + R)V_Z}{R_L} = \frac{(1200\ \Omega + 220\ \Omega)(20\ V)}{1200\ \Omega} = \mathbf{23.67\ V}$$

$$I_L = \frac{V_L}{R_L} = \frac{V_Z}{R_L} = \frac{20\ V}{1.2\ k\Omega} = 16.67\ mA$$

$$I_{R_{max}} = I_{ZM} + I_L = 60\ mA + 16.67\ mA$$

$$= 76.67\ mA$$

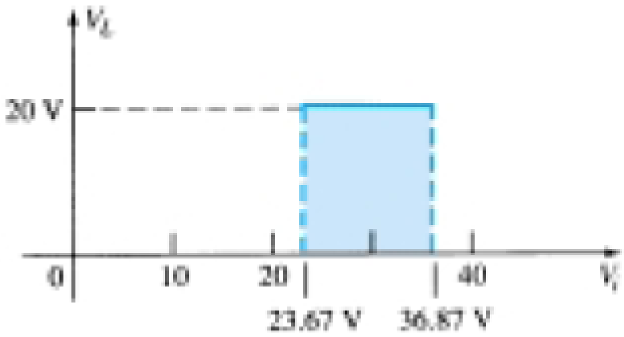
$$V_{i_{max}} = I_{R_{max}} R + V_Z$$

$$= (76.67\ mA)(0.22\ k\Omega) + 20\ V$$

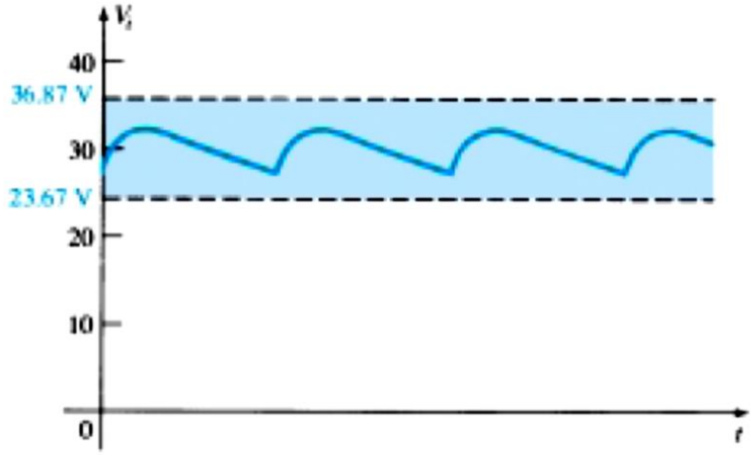
$$= 16.87\ V + 20\ V$$

$$= \mathbf{36.87\ V}$$

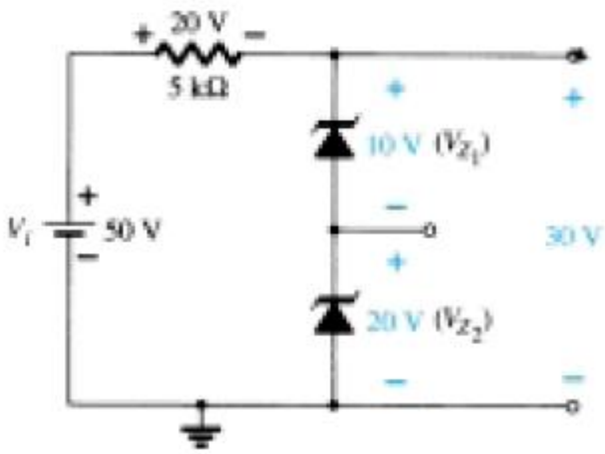
A plot of V_L versus Vi is provided in the figure below:



- The results of this example with a fixed *RL* revels that, the output voltage will remain fixed at 20 V for a range of input voltage that extends from 23.67 to 36.87 V.
- In fact, the input could appear as shown the figure below and the output would remain constant at 20 V.



- Two reference levels can be obtained using two Zener diodes as shown in the figure below, if the input voltage >V_{Z1}+V_{Z2}, both diodes are in ON state.



- Back to back Zener diodes can used to get the output as illustrated in the figures below:

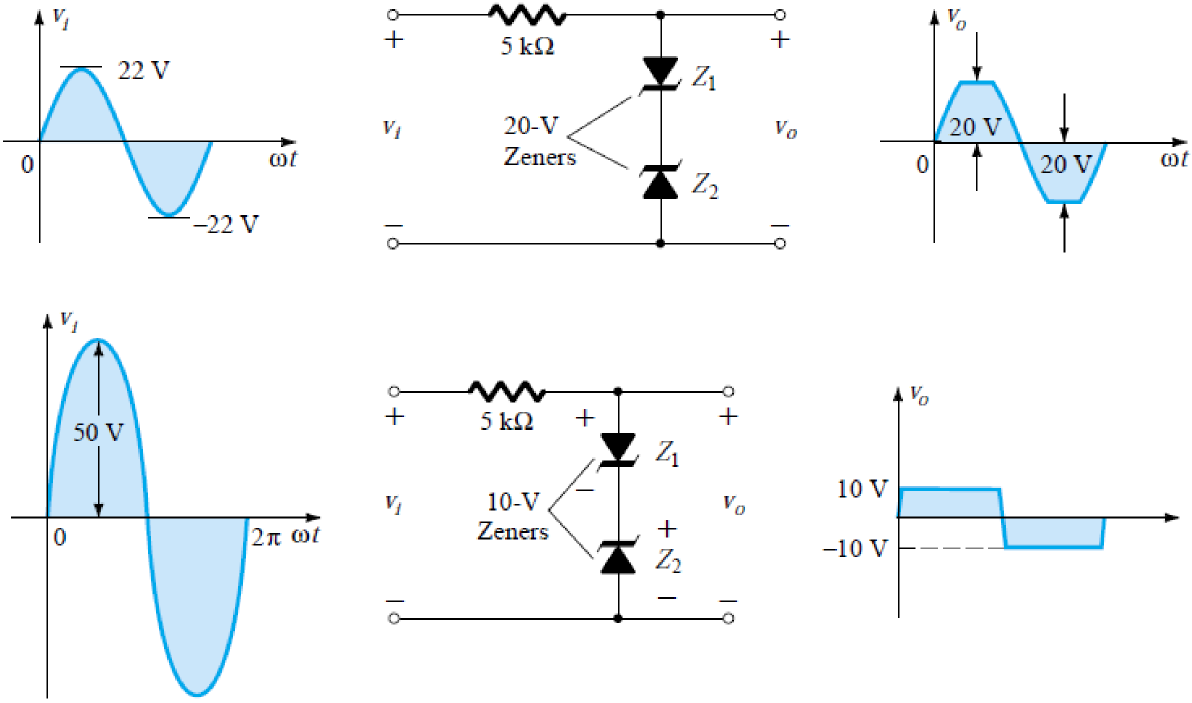


Figure: Output voltage and diode current waveforms: (a) small *C*; (b) large *C*.