Reference: Microelectronics circuit analysis and design by Donald Neamen

1.5.5 Zener Diode

As mentioned earlier in this chapter, the applied reverse-bias voltage cannot increase without limit. At some point, breakdown occurs and the current in the reverse-bias

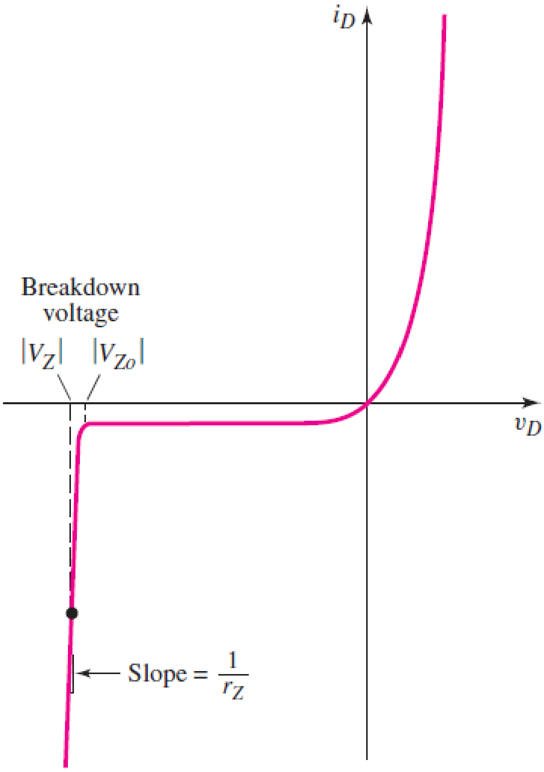


Figure 1.43 Diode *I–V* characteristics showing breakdown effects

direction increases rapidly. The voltage at this point is called the breakdown voltage. The diode *I–V* characteristics, including breakdown, are shown in Figure 1.43.

Diodes, called **Zener diodes,** can be designed and fabricated to provide a specified breakdown voltage V_{Zo}. (Although the breakdown voltage is on the negative voltage axis (reverse-bias), its value is given as a positive quantity.) The large current that may exist at breakdown can cause heating effects and catastrophic failure of the diode due to the large power dissipation in the device. However, diodes can be operated in the breakdown region by limiting the current to a value within the capabilities of the device. Such a diode can be used as a constant-voltage reference in a circuit. The diode breakdown voltage is essentially constant over a wide range of currents and temperatures. The slope of the *I–V* characteristics curve in breakdown is quite large, so the incremental resistance r_z is small. Typically, r_z is in the range of a few ohms or tens of ohms.

The circuit symbol of the Zener diode is shown in Figure 1.44. (Note the subtle difference between this symbol and the Schottky diode symbol.) The voltage V_Z is the Zener breakdown voltage, and the current I_Z is the reverse-bias current when the diode is operating in the breakdown region. We will see applications of the Zener diode in the next chapter.

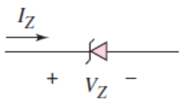


Figure 1.44 Circuit symbol of the Zener diode

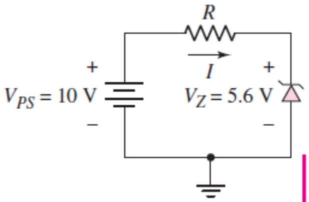


Figure 1.45 Simple circuit containing a Zener diode in which the Zener diode is biased in the breakdown region

DESIGN EXAMPLE 1.13

Objective: Consider a simple constant-voltage reference circuit and design the value of resistance required to limit the current in this circuit.

Consider the circuit shown in Figure 1.45. Assume that the Zener diode breakdown voltage is $V_Z = 5.6$ V and the Zener resistance is $r_z = 0$. The current in the diode is to be limited to 3 mA.

Solution: As before, we can determine the current from the voltage difference across *R* divided by the resistance. That is,

$$I = \frac{V_{PS} - V_Z}{R}$$

The resistance is then

$$R = \frac{V_{PS} - V_Z}{I} = \frac{10 - 5.6}{3} = 1.47\,\text{k}\Omega$$

The power dissipated in the Zener diode is

$$P_Z = I_Z V_Z = (3)(5.6) = 16.8\text{ mW}$$

The Zener diode must be able to dissipate 16.8 mW of power without being damaged.

Comment: The resistance external to the Zener diode limits the current when the diode is operating in the breakdown region. In the circuit shown in the figure, the output voltage will remain constant at 5.6 V, even though the power supply voltage and the resistance may change over a limited range. Hence, this circuit provides a constant output voltage.

Application of Zener diode : Zener diode as Voltage Regulator

2.2.1 Ideal Voltage Reference Circuit

Figure 2.16 shows a Zener voltage regulator circuit. For this circuit, the output voltage should remain constant, even when the output load resistance varies over a fairly wide range, and when the input voltage varies over a specific range. The variation in V_{PS} may be the ripple voltage from a rectifier circuit.

We determine, initially, the proper input resistance R_i. The resistance R_i limits the current through the Zener diode and drops the "excess" voltage between V_{PS} and V_Z. We can write

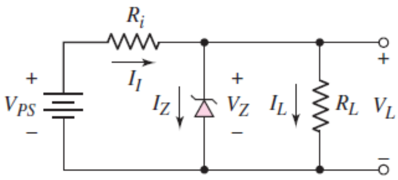


Figure 2.16 A Zener diode voltage regulator circuit

$$R_i = \frac{V_{PS} - V_Z}{I_I} = \frac{V_{PS} - V_Z}{I_Z + I_L} \quad (2.26)$$

which assumes that the Zener resistance is zero for the ideal diode. Solving this equation for the diode current, I_Z, we get

$$I_Z = \frac{V_{PS} - V_Z}{R_i} - I_L \quad (2.27)$$

where $I_L = V_Z/R_L$, and the variables are the input voltage source V_{PS} and the load current I_L.

For proper operation of this circuit, the diode must remain in the breakdown region and the power dissipation in the diode must not exceed its rated value. In other words:

1. The current in the diode is a minimum, $I_Z(\text{min})$, when the load current is a maximum, $I_L(\text{max})$, and the source voltage is a minimum, $V_{PS}(\text{min})$.
2. The current in the diode is a maximum, $I_Z(\text{max})$, when the load current is a minimum, $I_L(\text{min})$, and the source voltage is a maximum, $V_{PS}(\text{max})$.

Inserting these two specifications into Equation (2.26), we obtain

$$R_i = \frac{V_{PS}(\text{min}) - V_Z}{I_Z(\text{min}) + I_L(\text{max})} \quad (2.28(a))$$

and

$$R_i = \frac{V_{PS}(\text{max}) - V_Z}{I_Z(\text{max}) + I_L(\text{min})} \quad (2.28(b))$$

Equating these two expressions, we then obtain

$$[V_{PS}(\text{min}) - V_Z] \cdot [I_Z(\text{max}) + I_L(\text{min})] = [V_{PS}(\text{max}) - V_Z] \cdot [I_Z(\text{min}) + I_L(\text{max})] \quad (2.29)$$

Reasonably, we can assume that we know the range of input voltage, the range of output load current, and the Zener voltage. Equation (2.29) then contains two unknowns, $I_Z(\text{min})$ and $I_Z(\text{max})$. Further, as a minimum requirement, we can set the minimum Zener current to be one-tenth the maximum Zener current, or $I_Z(\text{min}) = 0.1 I_Z(\text{max})$. (More stringent design requirements may require the minimum Zener current to be 20 to 30 percent of the maximum value.) We can then solve for $I_Z(\text{max})$, using Equation (2.29), as follows:

$$I_Z(\text{max}) = \frac{I_L(\text{max}) \cdot [V_{PS}(\text{max}) - V_Z] - I_L(\text{min}) \cdot [V_{PS}(\text{min}) - V_Z]}{V_{PS}(\text{min}) - 0.9V_Z - 0.1V_{PS}(\text{max})} \quad (2.30)$$

Using the maximum current thus obtained from Equation (2.30), we can determine the maximum required power rating of the Zener diode. Then, combining Equation (2.30) with either Equation (2.28(a)) or (2.28(b)), we can determine the required value of the input resistance R_i.

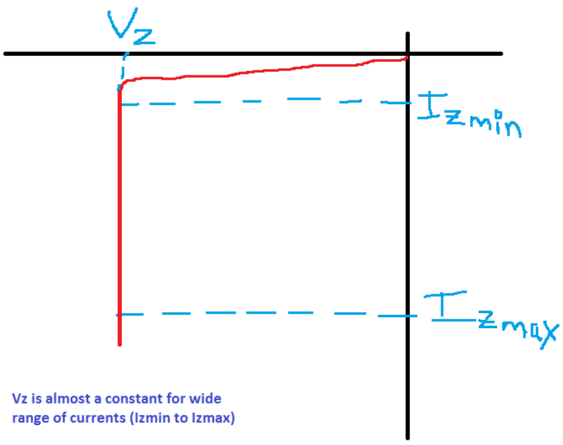
After writing these equations, please explain how Zener works as Voltage regulator for the following cases:

a) Source Variations : (If VPS may change and Load R_L is a constant)

1. If V_{PS} increases , then Ii should increase , but Ii = I_L + Iz , but since I_L remains constant as Load is constant , Iz has to increase. From reverse characteristics of Zener we see that if Iz remains less than Iz(max) then, the voltage across the zener I.e Vz almost does not change at all i.e VL remains constant i.e Output voltage remains constant in this case.

2. If V_{PS} decreases , then Ii should decrease as well , but Ii = I_L + Iz , but since I_L remains constant as Load is constant , Iz has to decrease. From reverse characteristics of Zener we see that if Iz remains greater than Iz(min) then, the voltage across the zener I.e Vz almost does not change at all i.e VL remains constant i.e Output voltage remains constant in this case.

(Draw Reverse I-V curve for Zener while explaining)



b) Load Variations : (If Load R_L is changes and source Vps is constant)

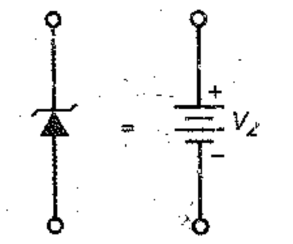
1. If Load R_L is of high value, then I_L will be smaller. But since Vps is not changing current Ii should remain constant. Also Ii = I_L + Iz, thus for Ii to be a constant, since I_L is reducing, zener current Iz has to increase (< Iz (max)). As we can notice from reverse curve of zener, even if Iz increases, still the voltage across zener is not changing much, i.e Vz almost does not change at all i.e VL remains constant i.e Output voltage remains constant in this case.

2. If Load R_L is of low value, then I_L will be a large value. But since Vps is not changing current Ii should remain constant. Also Ii = I_L + Iz, thus for Ii to be a constant, since I_L is increasing, zener current Iz has to decrease (> Iz (min)). As we can notice from reverse curve of zener, even if Iz decreases, still the voltage across zener is not changing much, i.e Vz almost does not change at all i.e V_L remains constant i.e Output voltage remains constant in this case.

The output voltage V_L of the circuit from fig 2.16 remains almost constant irrespective of the variations in the supply voltage and changes in the load current. Hence, the above circuit from fig 2.16 works as a Voltage Regulator.

Note : We have assumed for Above analysis , that Zener diode is ideal **(zener resistance**

Figure 5–3 Ideal approximation of a zener diode.



Below design example 2.5 is given for Reference study only: It helps in understanding voltage Regulation better

DESIGN EXAMPLE 2.5

Objective: Design a voltage regulator using the circuit in Figure 2.16.

The voltage regulator is to power a car radio at $V_L = 9$ V from an automobile battery whose voltage may vary between 11 and 13.6 V. The current in the radio will vary between 0 (off) to 100 mA (full volume).

The equivalent circuit is shown in Figure 2.17.

Solution: The maximum Zener diode current can be determined from Equation (2.30) as

$$I_Z(\text{max}) = \frac{(100)[13.6 - 9] - 0}{11 - (0.9)(9) - (0.1)(13.6)} \cong 300\,\text{mA}$$

The maximum power dissipated in the Zener diode is then

$$P_Z(\text{max}) = I_Z(\text{max}) \cdot V_Z = (300)(9) \Rightarrow 2.7\,\text{W}$$

The value of the current-limiting resistor R_i, from Equation (2.28(b)), is

$$R_i = \frac{13.6 - 9}{0.3 + 0} = 15.3\,\Omega$$

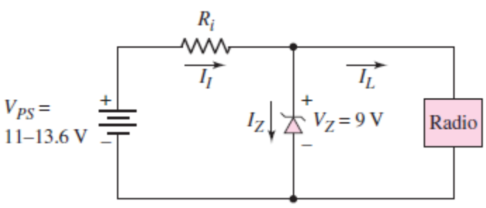


Figure 2.17 Circuit for Design Example 2.5

The maximum power dissipated in this resistor is

$$P_{Ri}(\text{max}) = \frac{(V_{PS}(\text{max}) - V_Z)^2}{R_i} = \frac{(13.6 - 9)^2}{15.3} \cong 1.4\,\text{W}$$

We find

$$I_Z(\text{min}) = \frac{11 - 9}{15.3} - 0.10 \Rightarrow 30.7\,\text{mA}$$

Comment: From this design, we see that the minimum power ratings of the Zener diode and input resistor are 2.7 W and 1.4 W, respectively. The minimum Zener diode current occurs for $V_{PS}(\text{min})$ and $I_L(\text{max})$. We find $I_Z(\text{min}) = 30.7$ mA, which is approximately 10 percent of $I_Z(\text{max})$ as specified by the design equations.

Design Pointer: (1) The variable input in this example was due to a variable battery voltage. However, referring back to Example 2.4, the variable input could also be a function of using a standard transformer with a given turns ratio as opposed to a custom design with a particular turns ratio and/or having a 120 V (rms) input voltage that is not exactly constant.

(2) The 9 V output is a result of using a 9 V Zener diode. However, a Zener diode with exactly a 9 V breakdown voltage may also not be available.