ZENER DIODES AND REGULATORS

INEL 4201 Electronics 1

Textbook section 4.4
4.2. Terminal Characteristics of Junction Diodes

- Most common implementation of a diode utilizes pn junction.
- $I$-$V$ curve consists of three characteristic regions:
  - forward bias: $v > 0$
  - reverse bias: $v < 0$
  - breakdown: $v << 0$

Discontinuity caused by differences in scale.
\[ i = I_s (e^{v/V_T} - 1) \]
Zener diodes
- reverse-bias operation
- keeps an approx. constant voltage independent of diode’s current
- Operation in this regime can destroy a regular diode
Voltage regulator

Let:

- $V_Z$: Zener diode’s nominal voltage.
- $i_{Z,\text{min}}$: minimum current through diode required for proper operation.
- $i_{L,\text{max}}, i_{L,\text{min}}$: maximum and minimum load’s current.
- $V_{S,\text{max}}, V_{S,\text{max}}$: maximum and minimum source voltage levels

- Minimum zener current $\geq i_{Z,\text{min}}$ when load current $= i_{L,\text{max}}$

- $V_Z$ is specified at a specific current; use piece-wise linear model to estimate the diode’s voltage at a different current
Slope = \frac{1}{r_z}

\Delta V = \Delta I r_z

- V_Z

- V_{Z_0}

- V_{Z_K}

0 - I_{Z_K}

- I_{Z_T} \text{ (test current)}
Voltage regulator

Let:

- $V_Z$: Zener diode’s nominal voltage.
- $i_{Z,min}$: minimum current through diode required for proper operation.
- $i_{L,max}, i_{L,min}$: maximum and minimum load’s current.
- $V_{S,max}, V_{S,min}$: maximum and minimum source voltage levels

For proper operation, select $R$ so that

$$R \leq \frac{V_{S,min} - V_Z}{i_{Z,min} + i_{L,max}}$$

Maximum power dissipated in the resistor:

$$P_{R,max} = \frac{(V_{S,max} - V_Z)^2}{R}$$

Maximum power dissipated in the diode:

$$P_{D,max} = V_Z \times \left( \frac{V_{S,max} - V_Z}{R} - i_{L,min} \right)$$

$D$ and $R$ must have a power rating greater than $P_{D,max}$ and $P_{R,max}$, respectively.
Analysis of Zener diode circuit using piecewise linear approximation:

1. Transform voltage source to current source then back to voltage source:

\[ V_{S}' = \frac{V_S}{R_1} (R_1 || R_L) = \frac{V_S}{R_1} \frac{R_1 \times R_L}{R_1 + R_L} = \frac{R_L}{R_1 + R_L} V_S \]

in series with a resistance \( R_1' = R_1 || R_L \).

2. Find diode’s current:

\[ i_D = \frac{V_{S}' - V_{Z0}}{R_1 || R_L + r_Z} \]

3. calculate \( V_L \) by finding voltage across diode:

\[ V_L = V_{Z0} + r_Z \times i_D \]
D 4.61 Design a 7.5-V zener regulator circuit using a 7.5-V zener specified at 12 mA. The zener has an incremental resistance $r_z = 30 \, \Omega$ and a knee current of 0.5 mA. The regulator operates from a 10-V supply and has a 1.2-k$\Omega$ load. What is the value of $R$ you have chosen? What is the regulator output voltage when the supply is 10% high? Is 10% low? What is the output voltage when both the supply is 10% high and the load is removed? What is the smallest possible load resistor that can be used while the zener operates at a current no lower than the knee current while the supply is 10% low? What is the load voltage in this case?
PROB. 4.61

• Design a regulator with output voltage \( V_L = 7.5V \)

• \( V_Z = 7.5V \) at \( I_Z = 12mA \), knee (minimum)
  current is 0.5mA, incremental resistance \( r_Z = 30\Omega \)

• Power Supply: \( V_{PS} = 10V \)

• Load: \( R_L = 1.2k\Omega \)
PROB. 4.61 | DESIGN

\[ I_L = \frac{7.5V}{1.2k\Omega} = 6.25mA \]

\[ I_R = I_L + I_Z = 12mA + 6.25mA = 18.25mA \]

\[ R = \frac{V_{PS} - V_L}{I_R} = \frac{10V - 7.5V}{18.25mA} \approx 137\Omega \]
WARNING: Diagram should show \( R = 137 \) instead of 139.5.

What’s the output voltage if the supply is 10% high?

\[
V_Z = I_Z \times 30\Omega + V_{Z0} \Rightarrow V_{Z0} = 7.5V - 12mA \times 30\Omega = 7.14V
\]

\[
\frac{V_{PS} - V_L}{R} = \frac{V_L - 7.14V}{30\Omega} + \frac{V_L}{R_L}
\]

\[
V_L = (R || 30\Omega || R_L) \left( \frac{V_{PS}}{R} + \frac{7.14V}{30\Omega} \right)
\]

For \( R = 137\Omega, V_{PS} = 10V \) and \( R_L = 1200\Omega \),

\[
V_L = (24.116\Omega) \left( \frac{10V}{137\Omega} + \frac{7.14V}{30\Omega} \right) = 7.5V
\]

as expected. For \( V_{PS} = 11V \),

\[
V_L = (24.116\Omega) \left( \frac{11V}{137\Omega} + \frac{7.14V}{30\Omega} \right) = 7.676V
\]
What’s the output voltage if the supply is 10% low?

\[ V_L = (24.116\Omega) \left( \frac{9V}{137\Omega} + \frac{7.14V}{30\Omega} \right) = 7.32V \]

What’s the output voltage if the load voltage is 10% high and the load is removed?

\[ V_L = (137\Omega || 30\Omega) \left( \frac{11V}{137\Omega} + \frac{7.14V}{30\Omega} \right) = 7.83V \]

What’s the smallest load resistor that will allow the zener to operate at \( I_{ZK} = 0.5mA \) if \( V_{PS} = 10V \)?

\[ V_Z = 7.14V + 0.5mA \times 30\Omega = 7.155V \]
\[ I_R = \frac{10V - 7.155V}{137\Omega} = 20.8mA \]
\[ I_L = 20.8mA - 0.5mA = 20.3mA \Rightarrow R_{L,\text{min}} = \frac{7.155V}{20.3mA} \approx 352\Omega \]