**Shunt Regulators**

The purpose of a voltage regulator is to keep the voltage at the "load" as constant as possible. Two separate things can cause the load voltage to change -- changes (including ripple) in the source voltage and changes in the load resistance. A simple voltage regulator can be made with a zener diode.

![Shunt regulator diagram]

Assume zener is conducting in breakdown region

\[ V_L = V_D = V_Z \]

\[ I_L = \frac{V_Z}{R_L} \]

\[ I_L = 20 \text{ mA} \]

\[ I_1 = \frac{V_S - V_Z}{R_1} \]

\[ I_1 = 50 \text{ mA} \]

Check

If you assumed conducting, then check current.

\[ I_D = I_1 - I_L \]

\[ I_D = 30 \text{ mA} \]

> 0, so assumption OK

What is the smallest \( V_S \) for which \( V_L \) remains "regulated"? Figure \( V_L \) and \( I_L \) and as above, now assume \( I_D = 0 \). Anything less than this and the regulator "drops out" of regulation.

\[ I_{1\text{min}} = I_L \]

\[ I_{1\text{min}} = 20 \text{ mA} \]

\[ V_{R1\text{min}} = I_{1\text{min}} \cdot R_1 \]

\[ V_{R1\text{min}} = 2 \cdot V \]

\[ V_{S\text{min}} = V_D + V_{R1\text{min}} \]

\[ V_{S\text{min}} = 12 \cdot V \]

Assuming \( V_S = 15\text{V} \) again, what is the smallest \( R_L \) for which the remains "in regulation". \( I_1 \) is as calculated before.

\[ I_{D\text{min}} = 0 \text{ mA} \]

\[ I_{L\text{max}} = I_1 \]

\[ R_{L\text{min}} = \frac{V_D}{I_{L\text{max}}} \]

\[ R_{L\text{min}} = 200 \text{ \Omega} \]

Of course these calculation assume an **ideal** zener diode which holds exactly the same reverse voltage regardless of the current, right down to 0 current. Oh, would that it were so easy...

**Non-ideal zener**

\[ V_Z = \text{Specified zener voltage} \]

\[ I_{ZT} = \text{The current required to get the specified zener voltage} \]

\[ r_Z = \text{The diode resistance, defined by the slope of the diode curve} \]

\[ V_{Z0} = \text{The smallest zener voltage due to} \ r_Z \text{ if there were no "knee"} \]

\[ V_{Z0} = V_Z - r_Z \cdot I_{ZT} \]

\[ I_{ZK} = \text{The knee current, the minimum current under which the diode voltage no longer considered "regulated"} \]

\[ V_{ZK} = \text{The knee voltage at} \ I_{ZK}. \]

Above the knee, we can model the diode as:
Let's say we have the specs for the diode:
\[ V_Z := 10 \text{ V at 50 mA, which means: } I_{ZT} := 50 \text{ mA} \]
\[ r_Z := 4 \Omega \quad I_{ZK} := 5 \text{ mA} \]
We need \( V_{Z0} \) to complete our model of the diode. This number is rarely given. Usually you'll have to calculate it.
\[ V_{Z0} := V_Z - I_{ZT} r_Z \quad V_{Z0} = 9.8 \text{ V} \]
This circuit can now be analyzed by superposition, Thevenin equivalent, or by nodal analysis. But we'll put that off for a minute and find the limit cases first, because they are a little easier.

What is the smallest \( V_S \) for which \( V_L \) remains "regulated"?
\[
V_{Dmin} := V_{Z0} + I_{ZK} r_Z \quad V_{Dmin} = 9.82 \text{ V} \\
I_{Lmin} := I_{ZK} + I_{Lmin} \quad I_{Lmin} = 24.64 \text{ mA} \\
I_{Lmax} := I_{Lmax} - I_{Dmin} \quad I_{Lmax} = 46.8 \text{ mA} \\
R_{Lmin} := V_{Dmin} / I_{Lmax} \quad R_{Lmin} = 209.8 \Omega
\]

Assuming \( V_S = 15 \text{ V} \) again, what is the smallest \( R_L \) for which the remains "in regulation".
\[
V_{Dmin} := V_{Z0} + I_{ZK} r_Z \quad V_{Dmin} = 9.82 \text{ V} \\
I_{Lmax} := I_{Lmax} - I_{Dmin} \quad I_{Lmax} = 46.8 \text{ mA} \\
R_{Lmin} := V_{Dmin} / I_{Lmax} \quad R_{Lmin} = 209.8 \Omega
\]

For the general analysis, make a Thevenin's equivalent
\[
V_S := 15 \text{ V} \\
R_1 := 100 \Omega \quad V_{Th} := \left( V_S - V_{Z0} \right) \frac{r_Z}{R_1 + r_Z} + V_{Z0} \\
R_{Th} := 3.846 \Omega \quad V_{Th} = 10 \text{ V}
\]

Now you can find the voltage across almost any load very quickly

**Regulation**

Load Regulation
\[
\frac{V_{L} - V_{IL}}{I_{IL} - I_{nL}} = \frac{\Delta V_L}{\Delta I_L} = \frac{-V_{R_{Th}}}{I_{L}} = -R_{Th} = - \frac{1}{\frac{1}{R_1} + \frac{1}{r_Z}}
\]

Line Regulation
\[
\Delta V_{S} = \frac{\Delta V_L}{\Delta V_S} = \frac{\Delta V_{Th}}{\Delta V_S} = \frac{d}{dV_S} \left( V_S - V_{Z0} \right) \frac{r_Z}{R_1 + r_Z} + V_{Z0} = \frac{r_Z}{R_1 + r_Z}
\]

no load current, or constant load current
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**Design**
Select a diode such that \( V_{Z0} > V_{L_{\text{min}}} \) required. Now design \( R_1 \) for the minimum \( R_L \) and minimum \( V_S \).

Let's say we select the diode:

\[
\begin{align*}
V_Z & := 10 \text{ V at 50 mA}, \quad \text{which means: } I_{ZT} := 50 \cdot \text{mA} \\
r_Z & := 4 \Omega \\
I_{ZK} & := 5 \cdot \text{mA}
\end{align*}
\]

We need \( V_{Z0} \) to complete our model of the diode. This number is rarely given. Usually you'll have to calculate it.

\[
\begin{align*}
V_{Z0} & := V_Z - I_{ZT} \cdot r_Z \\
I_{D_{\text{min}}} & := I_{ZK} \\
V_{D_{\text{min}}} & := V_{Z0} + I_{ZK} \cdot r_Z \\
I_1 & := I_{L_{\text{max}}} + I_{D_{\text{min}}} \\
R_1 & := \frac{V_S - V_{D_{\text{min}}}}{I_1}
\end{align*}
\]

Select the standard value of 72\( \Omega \) \( 105 \cdot \% \cdot 72 \cdot \Omega = 75.6 \cdot \Omega \) won't work in worst case

Select the standard value of \( R_1 := 68 \cdot \Omega \) \( 105 \cdot \% \cdot R_1 = 71.4 \cdot \Omega \) OK

Must check some power dissipations.

\[
P_{R1} = \frac{(V_{\text{Smax}} - V_{\text{Dmin}})^2}{R_1} = 0.758 \cdot \text{W}
\]

need a 1 watt \( R_1 \). Can be a combination of lower wattage resistors

What if \( R_L \) were removed?

\[
\begin{align*}
I_{Z_{\text{max}}} & := \frac{V_{\text{Smax}} - V_{Z0}}{R_1 + r_Z} \\
I_{Z_{\text{max}}} & := 100 \cdot \text{mA}
\end{align*}
\]

\[
P_{Z_{\text{max}}} = I_{Z_{\text{max}}}^2 \cdot V_{Z0} + I_{Z_{\text{max}}}^2 \cdot r_Z = 1.02 \cdot \text{W}
\]

need better than a 1 W zener

Can be two or more in series, but not in parallel, one \( V_Z \) will always be a little smaller and that diode will take the most current.

**Diode Equation** section 3.2 in book

Actually diode characteristic is a curve

**Diode Equation**

Diode current: \( I_d = I_s \left( \frac{V_d}{n \cdot V_{\text{TH}}} - 1 \right) \)

Saturation current

(AKA scale current)

Fudge factor, assume \( n = 1 \) in ICs and \( n = 2 \) for discrete parts

Other permutations of the diode equation:

\[
\begin{align*}
V_d & = n \cdot V_{\text{TH}} \ln \left( \frac{I_d}{I_s} \right) \\
I_s & = \frac{I_d}{\left( \frac{V_d}{n \cdot V_{\text{TH}}} - 1 \right)}
\end{align*}
\]

Absolute temperature: \( T = ^\circ \text{C} + 273 \)

Electron volt: \( eV := 1.60 \cdot 10^{-19} \cdot \text{Joule} \)

Boltzmann's constant: \( k := 8.63 \cdot 10^{-5} \cdot \frac{\text{eV}}{K} \)

Electron charge: \( q := 1.60 \cdot 10^{-19} \cdot \text{Coul} \)