A. Stolp
2/18/03

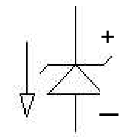
Stuff

HW #12, due M, 2/24 handout

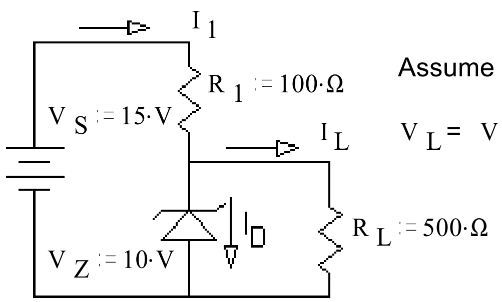
SPICE #S1, due W, 3/5 hw 12 handout

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.



V_Z = zener voltage



Shunt regulator

Assume zener is conducting in breakdown region

$V_L = V_D := V_Z$

$I_L := \frac{V_Z}{R_L}$ $\quad I_L = 20\cdot mA$

$I_1 := \frac{V_S - V_Z}{R_1}$ $\quad I_1 = 50\cdot mA$

Check If you assumed conducting, then check current.

$I_D := I_1 - I_L$ $\quad I_D = 30\cdot mA$ > 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.

$I_{1min} := I_L$ $\quad I_{1min} = 20\cdot mA$

$V_{R1min} := I_{1min}\cdot R_1$ $\quad V_{R1min} = 2\cdot V$

$V_{Smin} := V_D + V_{R1min}$ $\quad V_{Smin} = 12\cdot V$

Assuming V_S = 15V again, what is the smallest R_L for which the remains "in regulation". I_1 is as calculated before.

$I_{Dmin} := 0\cdot mA$ $\quad I_{Lmax} := I_1$ $\quad R_{Lmin} := \frac{V_D}{I_{Lmax}}$ $\quad R_{Lmin} = 200\cdot\Omega$

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 = Specified zener voltage

I_{ZT} = The current required to get the specified zener voltage

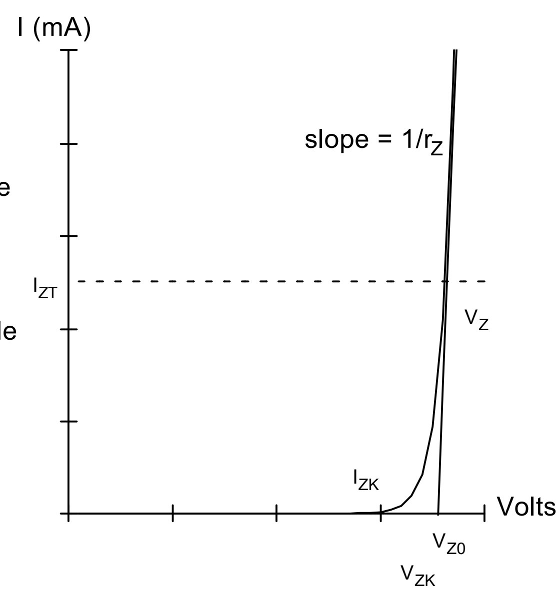
r_Z = The diode resistance, defined by the slope of the diode curve

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

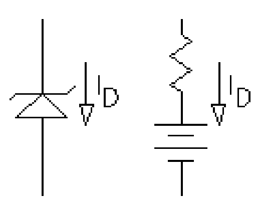
$V_{Z0} = V_Z - r_Z\cdot I_{ZT}$

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

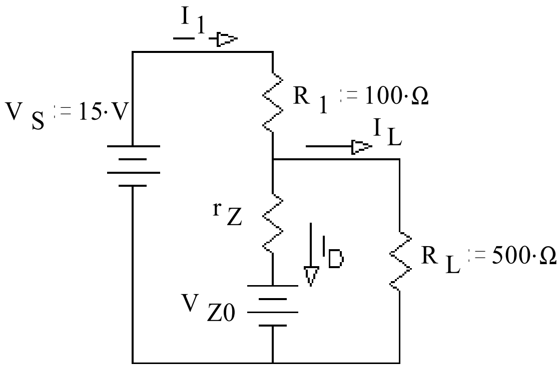
V_{ZK} = The knee voltage at I_{ZK}.



Above the knee, we can model the diode as:



Non-ideal shunt regulator



Shunt regulator

Let's say we have the specs for the diode:

$V_Z := 10 \cdot V$ at 50 mA, which means: $I_{ZT} := 50 \cdot mA$

$r_Z := 4 \cdot \Omega$ $\quad I_{ZK} := 5 \cdot mA$

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

$V_{Z0} := V_Z - I_{ZT} \cdot r_Z$ $\quad V_{Z0} = 9.8 \cdot V$

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"? $\quad I_{Dmin} := I_{ZK}$

$V_{Dmin} := V_{Z0} + I_{ZK} \cdot r_Z$ $\quad V_{Dmin} = 9.82 \cdot V$ $\quad I_{Lmin} := \frac{V_{Dmin}}{R_L}$ $\quad I_{Lmin} = 19.64 \cdot mA$

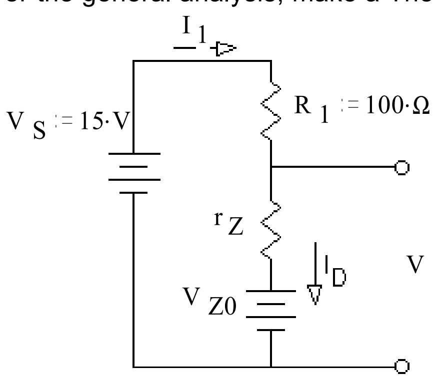
$I_{1min} := I_{ZK} + I_{Lmin}$ $\quad I_{1min} = 24.64 \cdot mA$ $\quad V_{Smin} := V_{Dmin} + I_{1min} \cdot R_1$ $\quad V_{Smin} = 12.284 \cdot V$

Assuming V_S = 15V again, what is the smallest R_L for which the remains "in regulation". $\quad I_{Dmin} := I_{ZK}$ again

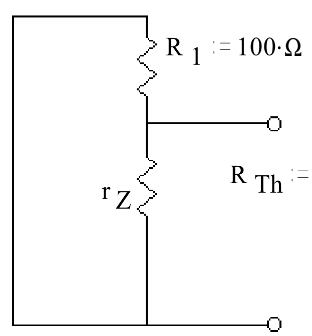
$V_{Dmin} := V_{Z0} + I_{ZK} \cdot r_Z$ $\quad V_{Dmin} = 9.82 \cdot V$ $\quad I_{1max} := \frac{V_S - V_{Dmin}}{R_1}$ $\quad I_{1max} = 51.8 \cdot mA$

$I_{Lmax} := I_{1max} - I_{Dmin}$ $\quad I_{Lmax} = 46.8 \cdot mA$ $\quad R_{Lmin} := \frac{V_{Dmin}}{I_{Lmax}}$ $\quad R_{Lmin} = 209.8 \cdot \Omega$

For the general analysis, make a Thevenin's equivalent

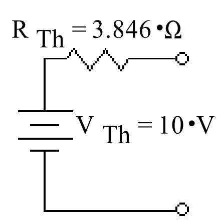


$$V_{Th} := (V_S - V_{Z0}) \cdot \frac{r_Z}{R_1 + r_Z} + V_{Z0}$$



$$R_{Th} := \frac{1}{\frac{1}{R_1} + \frac{1}{r_Z}}$$

If $R_1 >> r_Z$, then $R_{Th} \sim r_Z$



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

Regulation

Load Regulation $= \frac{V_{nL} - V_{fL}}{I_{fL} - I_{nL}} = \frac{\Delta V_L}{\Delta I_L} = \frac{-V_{RTh}}{I_L} = -R_{Th} = -\frac{1}{\frac{1}{R_1} + \frac{1}{r_Z}}$

Line Regulation $= \frac{V_{Lmax} - V_{Lmin}}{V_{Smax} - V_{Smin}} = \frac{\Delta V_L}{\Delta V_S} = \frac{\Delta V_{Th}}{\Delta V_S} = \frac{d}{dV_S}\left[(V_S - V_{Z0}) \cdot \frac{r_Z}{R_1 + r_Z} + V_{Z0}\right] = \frac{r_Z}{R_1 + r_Z}$

no load current, or constant load current

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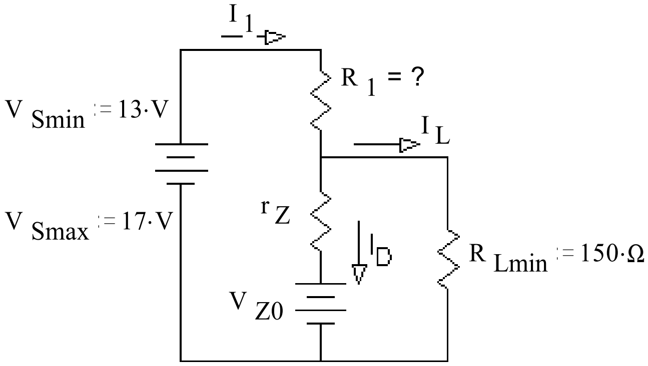
Design

Select a diode such the $V_{Z0} > V_{Lmin}$ required. Now design R_1 for the minimum R_L and minimum V_S.



Let's say we select the diode:

$V_Z := 10 \cdot V$ at 50 mA, which means: $I_{ZT} := 50 \cdot mA$

$r_Z := 4 \cdot \Omega$ $\quad I_{ZK} := 5 \cdot mA$

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

$V_{Z0} := V_Z - I_{ZT} \cdot r_Z$ $\qquad V_{Z0} = 9.8 \cdot V$

$I_{Dmin} := I_{ZK}$

$V_{Dmin} := V_{Z0} + I_{ZK} \cdot r_Z$ $\qquad V_{Dmin} = 9.82 \cdot V$

$I_{Lmax} := \frac{V_{Dmin}}{R_{Lmin}}$ $\qquad I_{Lmax} = 65.47 \cdot mA$

$I_1 := I_{Lmax} + I_{Dmin}$ $\qquad I_1 = 70.47 \cdot mA$

$R_1 := \frac{V_S - V_{Dmin}}{I_1}$ $\qquad R_1 = 73.5 \cdot \Omega$

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

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

Must check some power dissipations. $P_{R1} = \frac{(V_{Smax} - V_{Dmin})^2}{R_1} = 0.758 \cdot W$ need a 1 watt R_1. Can be a combination of lower wattage resistors

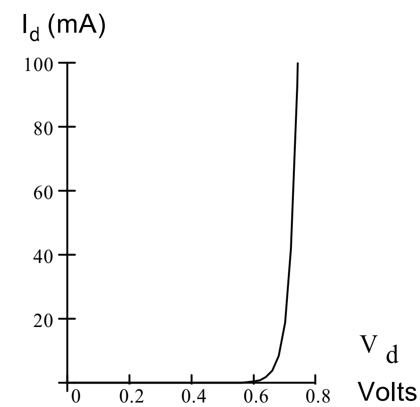
What if R_L were removed? $I_{Zmax} := \frac{V_{Smax} - V_{Z0}}{R_1 + r_Z}$ $\qquad I_{Zmax} = 100 \cdot mA$

$P_{Zmax} = I_{Zmax} \cdot V_{Z0} + I_{Zmax}{}^2 \cdot r_Z = 1.02 \cdot W$ 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 voltage

Diode current: $I_d = I_s \cdot \left(e^{\frac{V_d}{n \cdot V_T}} - 1 \right)$ Usually drop this 1 in forward bias

Saturation current
(AKA scale current)

Thermal voltage $= \frac{k \cdot T}{q} \cong 25 \cdot mV$

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

Other permutations of the diode equation:

$V_d = n \cdot V_T \cdot \ln\left(\frac{I_d}{I_s}\right)$ $\qquad I_s = \frac{I_d}{\left(e^{\frac{V_d}{n \cdot V_T}} - 1 \right)}$

Absolute temperature: T = °C + 273

Electron volt: $eV := 1.60 \cdot 10^{-19} \cdot joule$

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

Electron charge: $q := 1.60 \cdot 10^{-19} \cdot coul$