Lecture 13, Oct 20, 2023

Diode Shunt Regulator

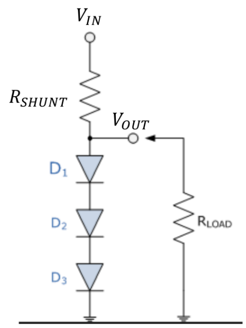

Figure 1: Diode shunt regulator circuit.

- The idea is that we're shunting the current that the load is not using through the diodes
- We expect this to have good line regulation since here V_{out} is essentially equal to the constant voltage drop across all the diodes
  - We can also design it for good load regulation
- Our operating condition are the same as the previous example:
  - Input voltage from 10-15V
  - Load current from 0-1A
  - Desired output is 9V
- We will modify the circuit to have 15 diodes in series instead of 3, all with a piecewise linear model; we will use a shut resistance of $R_{SHUNT} = 3.5\,\Omega$
- Since the diodes are all in series, they will share the same state, which we assume to be forward bias
  - Each diode is replaced with a constant voltage drop of $0.5\,\text{V}$ and a series resistance of $0.1\,\Omega$
  - This leads to a total voltage drop of $7.5\,\text{V}$ and resistance of $1.5\,\Omega$
- Line regulation: test two cases, $V_{IN} = 10\,\text{V}$ and $V_{IN} = 15\,\text{V}$, under a load current of $I_{LOAD} = 0\,\text{A}$
  - In this case the worst-case scenario is reached when the diodes are on the edge of being in reverse bias; this generally happens when we don't pull enough current or pull too much, but it is the former case that is more common
  - Node equation at output: $\dfrac{V_{OUT} - V_{IN}}{R_{SHUNT}} + I_LOAD + \dfrac{V_{OUT} - 7.5}{1.5} = 0$
  - At $V_{IN} = 10\,\text{V}, V_{OUT} = 8.25\,\text{V}$
  - At $V_{IN} = 15\,\text{V}, V_{OUT} = 9.75\,\text{V}$
  - The line regulation is $\dfrac{9.75 - 8.25}{9} = 16.7\%$, which is okay (but not very good)
    - The problem is that the design point for the circuit is different – the value of R_{SHUNT} is selected so that we can deliver larger currents; if we had chosen a larger resistance and limited our current range, we will see much better performance
- Load regulation: test two cases, $I_{LOAD} = 0\,\text{A}$ and $I_{LOAD} = 1\,\text{A}$, under an input voltage of $V_{IN} = 10\,\text{V}$
  - For pretty much all regulators without feedback, the worst case occurs with minimum input voltage; at minimum input voltage we're the most susceptible to losing forward bias on the diodes
    - This is referred to as the "dropout voltage", which is the minimum difference between V_{OUT} and V_{IN}
  - At $I_{LOAD} = 0\,\text{A}, V_{OUT} = 8.25\,\text{V}$
  - At $I_{LOAD} = 1\,\text{A}, V_{OUT} = 6.5\,\text{V}$
    - Note if we had assumed that the diodes are all in forward bias, we would have found $V_{OUT} = 7.25\,\text{V}$; this would mean less than $0.5\,\text{V}$ per diode, so we lose forward bias
    - In reverse bias we simply have $V_{OUT} = V_{IN} - R_{SHUNT} I_{LOAD} = 6.5\,\text{V}$
  - The load regulation is $\dfrac{8.25 - 6.5}{6.5} = 26.9\%$ which is quite bad

- This is a pretty good voltage regulator if we make sure that it does not drop out, so for higher current outputs we need to make sure that the input voltage stays high
- Note that in practice the power consumption of this circuit is quite high

Zener Diodes

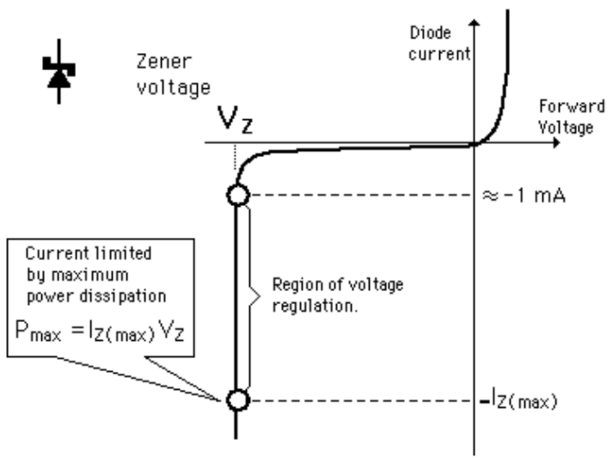

Figure 2: Model of a Zener diode.

- A zener diode is a diode engineered to undergo reverse breakdown non-destructively at a specific voltage
  - In forward bias it behaves similar to a regular diode, but in reverse we're able to get a very specific breakdown voltage that can be quite large
  - Typically zener diodes are used in reverse bias in its zener region
- Most often zener diodes are analyzed using a piecewise linear model; we will use a constant voltage model
  - We can replace a zener diode with just a constant voltage source, provided the reverse voltage is high enough
  - Note that because most diodes have a low voltage dissipation, for a larger zener voltage we will have very low current ratings
  - We neglect the linear resistance since most of the time we will have low current

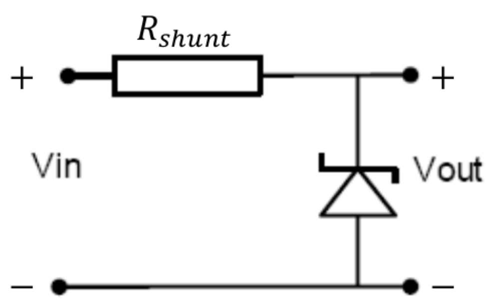

Figure 3: Example problem.

- Example: for the zener shunting regulator above, select the zener voltage V_Z and R_{SHUNT} and determine the current range it operates in; assume $V_{OUT} = 10\,\text{V}$ and V_{IN} is in the range of 12-18V, and the zener diode can dissipate 0.5W of power
  - If we use a constant voltage model we immediately see that $V_{OUT} = V_Z$, so we can select the zener voltage as 10V immediately

- The worst-case scenario for the input voltage is $V_{IN} = 18\,\text{V}$, which will give the highest current draw
    * Higher V_{IN} pushes more current through the shunt, which in the worst case will all go through the diode
    * Under this scenario and assuming $I_{LOAD} = 0\,\text{A}$ the diode dissipates a power of $V_{OUT}\frac{18 - V_{OUT}}{R_{SHUNT}} = 0.5\,\text{W}$, which we can solve to get $R_{SHUNT} = 160\,\Omega$
    * Note we always want to make R_{SHUNT} smaller because this limits the maximum amount of current we can draw
  - To see how much current we can draw, we need to consider the worst case V_{IN}
    * The critical point is when $\frac{V_{IN} - V_{OUT}}{R_{SHUNT}} \leq V_Z$ which is when the diode drops out
    * We also need $I_D \geq 0$ and $I_D = \frac{V_{IN} - V_Z}{R_{SHUNT}} - I_{LOAD}$; so when $V_{IN} = 12\,\text{V}$ and $I_D = 0$ we get a current limit of $12.5\,\text{mA}$ (which is higher for a higher V_{IN})
- Zener voltage references are the standard if we want to produce a precise voltage at a low current

Rectifier Circuits

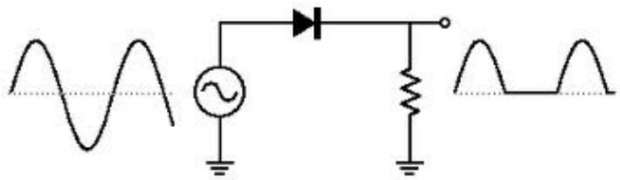

Figure 4: Example half-wave rectifier.

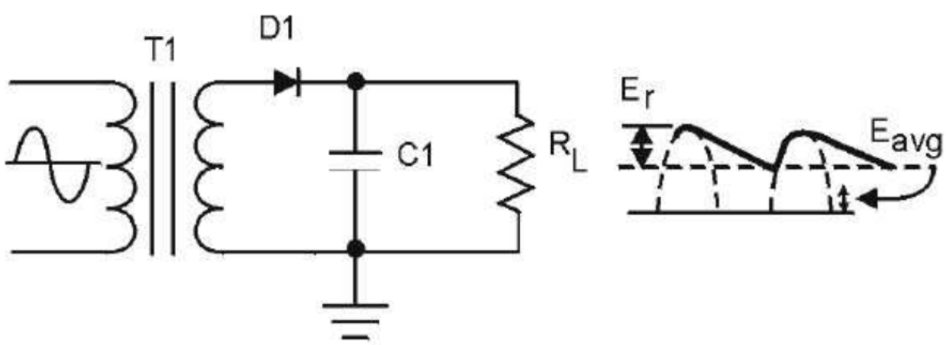

Figure 5: Half-way rectifier with capacitor.

- A rectifier circuit converts an input AC voltage into an output DC voltage
- In the example half-wave rectifier above, the diode will allow current to pass through whenever the AC voltage is positive, and block it when the voltage is negative
  - However this is produces an output that is far from DC since whenever the AC voltage goes negative, our DC voltage goes to zero
- To counteract this we use components that can store energy – capacitors and inductors; this will give us a wavelike output, which we can describe as DC plus some *ripple*
  - The amount of ripple is proportional to the current drawn and inversely proportional to the capacitance
  - Note that this puts a large reverse voltage on the diode, so we need to select the diode accordingly
  - If we attach a capacitor however, we get a large current spike when both the load and capacitor are getting current; therefore we need to make sure that the peak current rating for the diode is

high enough

  * This also increases the reverse voltage; in the worst case, we can see up to twice the original value