Regulator Power and Efficiency

Consider now the shunt regulator in terms of power.

The source $V_s$ delivers power $P_{in}$ to the regulator, and then the regulator in turn delivers power $P_L$ to the load.

A: Not hardly! The power delivered by the source is distributed to three devices—the load $R_L$, the zener diode, and the shunt resistor $R$.

Q: So, is the power delivered by the source equal to the power absorbed the load?
The power **delivered** by the **source** is:

\[ P_{in} = V_s i \]

\[ = V_s \left( \frac{V_s - V_{ZK}}{R} \right) \]

while the power **absorbed** by the **load** is:

\[ P_L = V_L i_L \]

\[ = V_{ZK} \left( \frac{V_{ZK}}{R_L} \right) \]

\[ = \frac{V_{ZK}^2}{R_L} \]

Thus, the power absorbed by the shunt resistor and zener diode combined is the difference of the two (i.e., \( P_{in} - P_L \)).

Note that the power absorbed by the load increases as \( R_L \) decreases (i.e., the load current increases as \( R_L \) decreases).

Recall that the load resistance can be arbitrarily large, but there is a **lower limit** on the value of \( R_L \), enforced by the condition:

\[ \frac{V_s R_L}{R + R_L} > V_{ZK} \]

Remember, if the above constraint is **not** satisfied, the zener will **not** breakdown, and the output voltage will drop **below** the desired regulated voltage \( V_{ZK} \)!
We can rewrite this constraint in terms of $R_L$:

$$R_L > \frac{V_{ZK} R}{V_s - V_{ZK}}$$

Rearranging the expression for load power (i.e., $P_L = \frac{V_{ZK}^2}{R_L}$):

$$R_L = \frac{V_{ZK}^2}{P_L}$$

we can likewise determine an upper bound on the power delivered to the load:

$$R_L = \frac{V_{ZK}^2}{P_L} > \frac{V_{ZK} R}{V_s - V_{ZK}}$$

and thus:

$$P_L < \frac{V_{ZK} (V_s - V_{ZK})}{R}$$

we can thus conclude that the maximum amount of power that can be delivered to the load (while keeping a regulated voltage) is:

$$P_L^{max} = \frac{V_{ZK} (V_s - V_{ZK})}{R}$$

which occurs when the load is at its minimum allowed value:

$$R_L^{min} = \frac{V_{ZK} R}{V_s - V_{ZK}}$$
Note, as \( R_L \) increases (i.e., \( i_L \) decreases), the load power decreases. As \( R_L \) approaches infinity (an open circuit), the load power becomes zero. Thus, we can state:

\[
0 \leq P_L \leq P_L^{\text{max}}
\]

Every voltage regulator (shunt or otherwise) will have a maximum load power rating \( P_L^{\text{max}} \). This effectively is the output power available to the load. Try to lower \( R_L \) (increase \( i_L \)) such that you exceed this rating, and one of two bad things may happen:

1) the regulated voltage will no longer be regulated, and drop below its nominal value.

2) the regulator will melt!

Now, contrast load power \( P_L \) with the input power \( P_{in} \):

\[
P_{in} = V_s \frac{(V_s - V_{zk})}{R}
\]

Q: Wait! It appears that the input power is independent of the load resistance \( R_L \)! Doesn’t that mean that \( P_{in} \) is independent of \( P_L \)?
A: That’s correct! The power flowing into the shunt regulator is constant, regardless of how much power is being delivered to the load.

In fact, even if $P_L=0$, the input power is still the same value shown above.

Q: But where does this input power go, if not delivered to the load?

A: Remember, the input power not delivered to the load must be absorbed by the shunt resistor $R$ and the zener diode. More specifically, as the load power $P_L$ decreases, the power absorbed by the zener must increase by an identical amount!

Q: Is this bad?

A: It sure is! Not only must we dissipate the heat that this power generates in the regulator, the energy absorbed by the shunt resistor and zener diode is essentially wasted.

This is particularly a concern if our source voltage $V_s$ is from a storage battery.

A storage battery holds only so much energy. To maximize the time before its depleted, we need to make sure that we use the energy effectively and efficiently.
Heating up a zener diode is not an efficient use of this limited energy!

Thus, another important parameter in evaluating regulator performance is its efficiency. Simply stated, regulator efficiency indicates the percentage of input power that is delivered to the load:

\[
\text{regulator efficiency } \quad e_r \doteq \frac{P_L}{P_{in}}
\]

Ideally, this efficiency value is \( e_r = 1 \), while the worst possible efficiency is \( e_r = 0 \).

For a shunt regulator, this efficiency is:

\[
e_r \doteq \frac{P_L}{P_{in}} = \frac{R}{R_L} \frac{V_{ZK}^2}{V_s (V_s - V_{ZK})}
\]

Note that this efficiency depends on the load value \( R_L \). As \( R_L \) increased toward infinity, the efficiency of the shunt regulator will plummet toward \( e_r = 0 \) (this is bad!).

On the other hand, the best possible efficiency occurs when \( P_L = P_L^{\max} \).
\[ e_r^{\text{max}} = \frac{P_L^{\text{max}}}{P_{\text{in}}} = \frac{V_{ZK}(V_s - V_{ZK})}{R} \left( \frac{R}{V_s(V_s - V_{ZK})} \right) = \frac{V_{ZK}}{V_s} \]

Thus, for the shunt regulator design we have studied, the efficiency is:

\[ 0 \leq e_r \leq \left( \frac{V_{ZK}}{V_s} \right) \]

**Q:** So, to increase regulator efficiency, we should make \( V_s \) as small as possible?

**A:** That would in fact improve regulator efficiency, but beware! Reducing \( V_s \) will likewise lower the maximum possible load power \( P_L^{\text{max}} \).