3.4 Operation in the Reverse Breakdown Region — Zener Diodes

Reading Assignment: pp. 167-171

A Zener Diode ⇒ 

The 3 technical differences between a junction diode and a Zener diode:

1. 

2. 

3. 

The practical difference between a Zener diode and “normal” junction diodes:

⇒ Manufacturer assumes diode will be operated in breakdown region. Therefore:
1. 

2. 

3. 

**HO: Zener Diode Notation**

A. **Zener Diode Models**

**Q:** How do we analyze zener diodes circuits?

**A:** Same as junction diode circuits—

Big problem -> 

Big solution ->

**HO: Zener Diode Models**

**Example: Fun with Zener Diodes**
B. Voltage Regulation

Say that we have a 20 V supply but need to place 10 V across some load:

\[
\begin{align*}
&\text{20 V} \\
&\text{10 V} \quad R_L \\
\end{align*}
\]

The solution seems easy! →

\[
\begin{align*}
&\text{20 V} \\
&\text{10 V} \quad R_L \\
\end{align*}
\]

This, in fact is a very bad solution—

HO: The Shunt Regulator
Two primary measures of voltage regulator effectiveness are line regulation and load regulation.

**HO: Line Regulation**

**HO: Load Regulation**

**Example: The Shunt Regulator**

Another important aspect of voltage regulation is power efficiency!

**Regulator Power and Efficiency**

One last point; voltage regulation can (and is) achieved by other means.

**Voltage Regulators**
Zener Diode Notation

To distinguish a zener diode from conventional junction diodes, we use a modified diode symbol:

\[ \text{Anode} \rightarrow \text{Cathode} \]

Generally speaking, a zener diode will be operating in either breakdown or reverse bias mode.

For both these two operating regions, the cathode voltage will be greater than the anode voltage, i.e.:

\[ v_D < 0 \quad (\text{for r.b. and bd}) \]

Likewise, the diode current (although often tiny) will flow from cathode to anode for these two modes:

\[ i_D < 0 \quad (\text{for r.b. and bd}) \]

Q: Yikes! Won’t the the numerical values of both \( i_D \) and \( v_D \) be negative for a zener diode (assuming only rb and b.d. modes).

A: With the standard diode notation, this is true. Thus, to avoid negative values in our circuit computations, we are going to change the definitions of diode current and voltage!
In other words, for a Zener diode, we denote current flowing from cathode to anode as positive.

Likewise, we denote diode voltage as the potential at the cathode with respect to the potential at the anode.

Note that each of the above two statements are precisely opposite to the “conventional” junction diode notation that we have used thus far:

\[ v_Z = -v_D \quad \text{and} \quad i_Z = -i_D \]

Two ways of expressing the same junction diode curve.
The $i_Z$ versus $V_Z$ curve for a zener diode is therefore:

Thus, in **forward bias** (as unlikely as this is):

\[
i_Z = -I_s \exp\left(\frac{-V_Z}{nV_T}\right)
\]

or approximately:

\[
V_Z \approx -0.7 \text{ V and } i_Z < 0
\]
Likewise, in reverse bias:

\[ i_Z \approx I_s \quad \text{and} \quad 0 < v_Z < V_{ZK} \]

And finally, for breakdown:

\[ i_Z > 0 \quad \text{and} \quad v_Z \approx V_{ZK} \]
Zener Diode Models

The conventional diode models we studied earlier were based on junction diode behavior in the forward and reverse bias regions—they did not “match” the junction diode behavior in breakdown!

However, we assume that Zener diodes most often operate in breakdown—we need new diode models!

Specifically, we need models that match junction/Zener diode behavior in the reverse bias and breakdown regions.
We will study two important zener diode models, each with familiar names!

1. The Constant Voltage Drop (CVD) Zener Model
2. The Piece-Wise Linear (PWL) Zener Model

**The Zener CVD Model**

Let's see, we know that a Zener Diode in reverse bias can be described as:

\[ i_Z \approx I_s \approx 0 \quad \text{and} \quad v_Z < V_{ZK} \]

Whereas a Zener in breakdown is approximately stated as:

\[ i_Z > 0 \quad \text{and} \quad v_Z \approx V_{ZK} \]

**Q:** Can we construct a model which behaves in a similar manner??

**A:** Yes! The **Zener CVD model** behaves precisely in this way!

Replace: 

\[ i_Z \quad v_Z \]

With:

\[ i_Z \quad V_{ZK} \quad v_Z \]

Note the direction of ideal diode!
Analyzing this Zener CVD model, we find that if the model voltage $v_Z$ is less than $V_{ZK}$ (i.e., $v_Z < V_{ZK}$), then the ideal diode will be in reverse bias, and thus the model current $i_Z$ will equal zero. In other words:

$$i_Z = 0 \quad \text{and} \quad v_Z < V_{ZK}$$

Just like a Zener diode in reverse bias!

Likewise, we find that if the model current is positive ($i_Z > 0$), then the ideal diode must be forward biased, and thus the model voltage must be $v_Z = V_{ZK}$. In other words:

$$i_Z > 0 \quad \text{and} \quad v_Z = V_{ZK}$$

Just like a Zener diode in breakdown!

**Problem:** The voltage across a zener diode in breakdown is NOT EXACTLY equal to $V_{ZK}$ for all $i_Z > 0$. The CVD is an approximation.
In reality, $v_Z$ increases a very small (tiny) amount as $i_Z$ increases.

Thus, the CVD model causes a small error, usually acceptable—but for some cases not!

For these cases, we require a better model:

→ The Zener (PWL) Piece-Wise Linear model.

**The Zener Piecewise Linear Model**

Replace: with:

**Zener PWL Model**
Please Note:

* The PWL model includes a very small series resistor, such that the voltage across the model \( v_z \) increases slightly with increasing \( i_z \).

* This small resistance \( r_Z \) is called the dynamic resistance.

* The voltage source \( V_{Z0} \) is not equal to the zener breakdown voltage \( V_{ZK} \), however, it is typically very close!

Just like a Zener diode in reverse bias!

Likewise, we find that if the model current is positive (\( i_Z > 0 \)), then the ideal diode must be forward biased, and thus:

\[ i_Z > 0 \quad \text{and} \quad v_z = V_{Z0} + i_z r_Z \]

Note that the model voltage \( v_z \) will be near \( V_{ZK} \), but will increase slightly as the model current increases.

Just like a Zener diode in breakdown!
Comparison between CVD and PWL models

Q: How do we construct this PWL model (i.e., find $V_{Z0}$ and $r_z$)?

A: Pick two points on the zener diode curve $(v_1, i_1)$ and $(v_2, i_2)$, and then select $r_z$ and $V_{Z0}$ so that the PWL model line intersects them.

$$r_z = \frac{v_2 - v_1}{i_2 - i_1}$$

and

$$V_{Z0} = v_1 - i_1 r_z \quad \text{or} \quad V_{Z0} = v_2 - i_2 r_z$$
Consider this circuit, which includes a zener diode:

Let's see if we can determine the voltage across and current through the zener diode!

First, we must replace the zener diode with an appropriate model. Assuming that the zener will either be in breakdown or reverse bias, a good choice would be the zener CVD model.

Carefully replacing the zener diode with this model, we find that we are left with an IDEAL diode circuit:
Since this is an IDEAL diode circuit, we know how to analyze it!

Q: But wait! The ideal diode in this circuit is part of a zener diode model. Don’t we need to thus modify our ideal diode circuit analysis procedure in some way? In order to account for the zener diode behavior, shouldn’t we alter what we assume, or what we enforce, or what we check?

A: NO! There are no zener diodes in the circuit above! We must analyze this ideal diode circuit in precisely the same way as we have always analyzed ideal diode circuits (i.e., section 3.1).
**ASSUME:** Ideal diode is forward biased.

**ENFORCE:** \( v_D^i = 0 \)

**ANALYZE:**

From KVL:

\[
17 - v_D^i - 20 - i_2 (1) = 0
\]

\[
\therefore i_2 = \frac{17 - 0 - 20}{1} = -3.0 \text{ mA}
\]

Likewise from KVL:

\[
17 - v_D^i - 20 + i_1 (4) = 10
\]

\[
i_1 = \frac{10 + 20 + 0 - 17}{4} = 3.25 \text{ mA}
\]

Now from KCL:
\[ i'_D = i_2 - i_1 - 5.0 \]
\[ = -3.0 - 3.25 - 5.0 = -11.25 \text{ mA} \]

**CHECK:** \[ i'_D = -11.25 \text{ mA} < 0 \] \( \times \)

Yikes! We must change our ideal diode assumption and try again.

**ASSUME:** Ideal diode is reverse biased.

**ENFORCE:** \[ i'_D = 0 \]

**ANALYZE:**

From KCL:
\[ i_2 = i_1 + 5 \]

From KVL:
\[ 10.0 - i_1(4) - i_2(1) = 0 \]

\[ \therefore 10.0 - i_1(4) - (i_1 + 5)(1) = 0 \]

\[ \therefore i_1 = \frac{10 - 5}{4 + 1} = 1 \text{ mA} \]

Now, again using KVL:

\[ 17 - v_D' - 20 + i_1(4) = 10 \]

\[ v_D' = 17 - 20 + (1)(4) - 10 \]

\[ = -11.0 \text{ V} \]

**CHECK**: \[ v_D' = -11.0 \text{ V} < 0 \checkmark \]

**Q**: Our assumption is good! Since our analysis is complete, can we move on to something else?

**A**: Not so fast! Remember, we are attempting to find the voltage across, and current through, the zener diode.

To (approximately) determine these values, we find the voltage across, and current through, the zener diode model.
So,
\[ V_Z = V_D + V_{ZK} \]
\[ = -11 + 20 \]
\[ = 9.0 \text{ V} \]
and
\[ i_Z = i_D = 0 \]
We're done!

Q: Wait! Don't we have to somehow CHECK these values?

A: NO! We assumed nothing about the zener diode, we enforced nothing about the zener diode, and thus there is nothing to explicitly check in regards to the zener diode solutions.

However—like all engineering analysis—we should perform a "sanity check" to see if our answer makes physical sense.

So, let me ask you the question Q: Does this answer make physical sense?

A:
The Shunt Regulator

The shunt regulator is a voltage regulator. That is, a device that keeps the voltage across some load resistor \( R_L \) constant.

**Q:** Why would this voltage not be a constant?

**A:** Two reasons:

1. the source voltage \( V_s \) may vary and change with time.
2. The load \( R_L \) may also vary and change with time. In other words, the current \( i_L \) delivered to the load may change.

What can we do to keep load voltage \( V_0 \) constant?

⇒ Employ a Zener diode in a shunt regulator circuit!
Let's analyze the shunt regulator circuit in terms of Zener breakdown voltage $V_{ZK}$, source voltage $V_S$, and load resistor $R_L$.

Replacing the Zener diode with a Zener CVD model, we **assume** the ideal diode is forward biased, and thus **enforce** $v_d = 0$.

**ANALYZE:**

From KVL:

$$v_Z = V_O = v_d + V_{ZK} = V_{ZK}$$

From KCL:

$$i = i_d + i_L$$

where from Ohm's Law:

$$i = \frac{V_s - V_{ZK}}{R}$$
and also:

\[ i_L = \frac{V_{ZK}}{R_L} \]

Therefore:

\[ i_D^i = i - i_L \]

\[ = \frac{V_S - V_{ZK}}{R} - \frac{V_{ZK}}{R_L} \]

\[ = \frac{V_S}{R} - \frac{V_{ZK}(R + R_L)}{RR_L} \]

**CHECK:**

Note we find that ideal diode is forward biased if:

\[ i_D^i = \frac{V_S}{R} - \frac{V_{ZK}(R + R_L)}{RR_L} > 0 \]

or therefore:

\[ \frac{V_S}{R} - \frac{V_{ZK}(R + R_L)}{RR_L} > 0 \]

\[ \Rightarrow \frac{V_S}{R} > \frac{V_{ZK}(R + R_L)}{RR_L} \]

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

Hence, the Zener diode may **not** be in breakdown (i.e., the ideal diode may not be f.b.) if \( V_S \) or \( R_L \) are too small, or shunt resistor \( R \) is too large!
Summarizing, we find that if:

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

then:

1. The Zener diode is in breakdown.
2. The load voltage \( V_O = V_{ZK} \).
3. The load current is \( i_L = V_{ZK} / R_L \).
4. The current through the shunt resistor \( R \) is \( i = (V_S - V_{ZK}) / R \).
5. The current through the Zener diode is \( i_Z = i - i_L > 0 \).

We find then, that if the source voltage \( V_S \) increases, the current \( i \) through shunt resistor \( R \) will likewise increase. However, this extra current will result in an equal increase in the Zener diode current \( i_Z \)—thus the load current (and therefore load voltage \( V_O \)) will remain unchanged!
Similarly, if the load current $i_L$ increases (i.e., $R_L$ decreases), then the Zener current $i_Z$ will decrease by an equal amount. As a result, the current through shunt resistor $R$ (and therefore the load voltage $V_O$) will remain unchanged!

**Q:** You mean that $V_O$ stays perfectly constant, regardless of source voltage $V_S$ or load current $i_L$??

**A:** Well, $V_O$ remains approximately constant, but it will change a tiny amount when $V_S$ or $i_L$ changes.

To determine precisely how much the load voltage $V_O$ changes, we will need to use a more precise Zener diode model (i.e., the Zener PWL)!
Line Regulation

Since the Zener diode in a shunt regulator has some small (but non-zero) dynamic resistance $r_Z$, we find that the load voltage $V_O$ will have a small dependence on source voltage $V_S$.

In other words, if the source voltage $V_S$ increases (decreases), the load voltage $V_O$ will likewise increase (decrease) by some very small amount.

Q: Why would the source voltage $V_S$ ever change?

A: There are many reasons why $V_S$ will not be a perfect constant with time. Among them are:

1. Thermal noise
2. Temperature drift
3. Coupled 60 Hz signals (or digital clock signals)

As a result, it is more appropriate to represent the total source voltage as a time-varying signal ($v_S(t)$), consisting of both a DC component ($V_S$) and a small-signal component ($\Delta v_S(t)$):

$$v_S(t) = V_S + \Delta v_S(t)$$
As a result of the small-signal source voltage, the total load voltage is likewise time-varying, with both a DC \( (V_O) \) and small-signal \( (\Delta v_o) \) component:

\[
v_o(t) = V_O + \Delta v_o(t)
\]

So, we know that the DC source \( V_S \) produces the DC load voltage \( V_O \), whereas the small-signal source voltage \( \Delta v_s \) results in the small-signal load voltage \( \Delta v_o \).

Q: Just how are \( \Delta v_s \) and \( \Delta v_o \) related? I mean, if \( \Delta v_s \) equals, say, 500 mV, what will value of \( \Delta v_o \) be?

A: Determining this answer is easy! We simply need to perform a small-signal analysis.

In other words, we first replace the Zener diode with its Zener PWL model.
We then turn off all the DC sources (including $V_{ZO}$) and analyze the remaining small-signal circuit!

From voltage division, we find: 

$$\Delta V_o = \Delta V_s \left( \frac{r_Z R_L}{R + r_Z R_L} \right)$$

However, recall that the value of a Zener dynamic resistance $r_Z$ is very small. Thus, we can assume that $r_Z \gg R_L$, and therefore $r_Z R_L \approx r_Z$, leading to:
\[ \Delta V_o = \Delta V_s \left( \frac{r_Z \| R_L}{R + r_Z \| R_L} \right) \]

\[ \approx \Delta V_s \left( \frac{r_Z}{r_Z + R} \right) \]

Rearranging, we find:

\[ \frac{\Delta V_o}{\Delta V_s} = \frac{r_Z}{r_Z + R} \equiv \text{line regulation} \]

This equation describes an important performance parameter for shunt regulators. We call this parameter the line regulation.

* Line regulation allows us to determine the amount that the load voltage changes (\( \Delta V_o \)) when the source voltage changes (\( \Delta V_s \)).

* For example, if line regulation is 0.002, we find that the load voltage will increase 1 mV when the source voltage increases 500 mV (i.e., \( \Delta V_o = 0.002 \Delta V_s = 0.002(0.5) = 0.001 \text{ V} \)).

* **Ideally**, line regulation is zero. Since dynamic resistance \( r_Z \) is typically very small (i.e., \( r_Z \ll R \)), we find that the line regulation of most shunt regulators is likewise small (this is a good thing!).
For voltage regulators, we typically define a load $R_L$ in terms of its current $i_L$, where:

$$i_L = \frac{v_o}{R_L}$$

Note that since the load (i.e., regulator) voltage $v_o$ is a constant (approximately), specifying $i_L$ is equivalent to specifying $R_L$, and vice versa!

Now, since the Zener diode in a shunt regulator has some small (but non-zero) dynamic resistance $r_Z$, we find that the load voltage $v_o$ will also have a very small dependence on load resistance $R_L$ (or equivalently, load current $i_L$).

In fact, if the load current $i_L$ increases (decreases), the load voltage $v_o$ will actually decrease (increase) by some small amount.

**Q:** Why would the load current $i_L$ ever change?
A: You must realize that the load resistor $R_L$ simply models a more useful device. The “load” may in fact be an amplifier, or a component of a cell phone, or a circuit board in a digital computer.

These are all dynamic devices, such that they may require more current at some times than at others (e.g., the computational load increases, or the cell phone begins to transmit).

As a result, it is more appropriate to represent the total load current as a time-varying signal ($i_L(t)$), consisting of both a DC component ($I_L$) and a small-signal component ($\Delta i_L(t)$):

$$i_L(t) = I_L + \Delta i_L(t)$$

This small-signal load current of course leads to a load voltage that is likewise time-varying, with both a DC ($V_O$) and small-signal ($\Delta V_o$) component:

$$V_O(t) = V_O + \Delta V_o(t)$$

So, we know that the DC load current $I_L$ produces the DC load voltage $V_O$, whereas the small-signal load current $\Delta i_L(t)$ results in the small-signal load voltage $\Delta V_o$.

We can replace the load resistor with current sources to represent this load current:
Q: Just how are $\Delta i_L$ and $\Delta v_o$ related? I mean, if $\Delta i_L$ equals, say, 50 mA, what will value of $\Delta v_o$ be?

A: Determining this answer is easy! We simply need to perform a small-signal analysis.

In other words, we first replace the Zener diode with its Zener PWL model.
We then turn off all the DC sources (including $V_{ZO}$) and analyze the remaining small-signal circuit!

From Ohm's Law, it is evident that:

$$
\Delta v_o = -\Delta i_L (r_Z || R) \\
= -\Delta i_L \left( \frac{r_Z R}{r_Z + R} \right)
$$

Rearranging, we find:

$$load\ regulation \doteq \frac{\Delta v_o}{\Delta i_L} = -\frac{r_Z R}{r_Z + R} = -r_Z || R \approx -r_Z \quad [Ohm's]\$$

This equation describes an important performance parameter for shunt regulators. We call this parameter the load regulation.
* Note load regulation is expressed in units of resistance (e.g., Ω).

* Note also that load regulation is a negative value. This means that increasing $i_L$ leads to a decreasing $v_O$ (and vice versa).

* Load regulation allows us to determine the amount that the load voltage changes ($\Delta v_o$) when the load current changes ($\Delta i_L$).

* For example, if load regulation is -0.0005 KΩ, we find that the load voltage will decrease 25 mV when the load current increases 50mA (i.e., $\Delta v_o = -0.0005 \Delta i_L = -0.0005(50) = -0.025$ V).

* Ideally, load regulation is zero. Since dynamic resistance $r_Z$ is typically very small (i.e., $r_Z \ll R$), we find that the load regulation of most shunt regulators is likewise small (this is a good thing!).
Example: The Shunt Regulator

Consider the shunt regulator, built using a zener diode with $V_{ZK}=15.0\text{ V}$ and incremental resistance $r_z=5\Omega$:

1. **Determine** $R$ if the largest possible value of $i_L$ is 20 mA.

2. Using the value of $R$ found in part 1 **determine** $i_Z$ if $R_L=1.5\text{ K}$.

3. Determine the change in $v_O$ if $V_S$ increases one volt.

4. Determine the change in $v_O$ if $i_L$ increases 1 mA.
**Part 1:**

From KCL we know that \( i = i_Z + i_L \).

We also know that for the diode to remain in breakdown, the zener current must be positive.

\[
i_Z = i - i_L > 0
\]

Therefore, if \( i_L \) can be as large as 20 mA, then \( i \) must be greater than 20 mA for \( i_Z \) to remain greater than zero.

\[
i > 20\text{mA}
\]

**Q:** But, what is \( i \)??

**A:** Use the zener CVD model to analyze the circuit.
Therefore from Ohm's Law:

\[ i = \frac{V_S - V_{ZK}}{R} = \frac{25 - 15}{R} = \frac{10}{R} \]

and thus \( i > 20 \text{mA} \) if:

\[ R < \frac{10}{20} = 0.5 \text{ K} = 500 \Omega \]

Note we want \( R \) to be as large as possible, as large \( R \) improves both line and load regulation.

Therefore, set \( R = 500 \Omega = 0.5 \text{ K} \)

**Part 2:**

Again, use the zener CVD model, and enforce \( v_D^i = 0 \):

\[ i_D^i = i - i_L \]
and from Ohm's Law:

\[ i = \frac{V_s - V_{zk}}{R} = \frac{25.0 - 15.0}{0.5} = 20.0 \text{ mA} \]

\[ i_L = \frac{V_{zk}}{R_L} = \frac{15.0}{1.5} = 10.0 \text{ mA} \]

Therefore \( i_d' = i - i_L = 20 - 10 = 10.0 \text{ mA} \) (\( i_d' = 10 > 0 \) ✓)

And thus we estimate \( i_Z = i_d' = 10.0 \text{ mA} \)

**Part 3:**

The shunt regulator **line regulation** is:

\[ \text{Line Regulation} = \frac{r_z}{R + r_z} = \frac{5}{500 + 5} = 0.01 \]

Therefore if \( \Delta v_s = 1 \text{ V} \), then \( \Delta v_o = (0.01) \Delta v_s = 0.01 \text{ V} \)

**Part 4:**

The shunt regulator **load regulation** is:

\[ \text{Load Regulation} = -\frac{R \cdot r_z}{R + r_z} = -\frac{(500)5}{500 + 5} = -4.95 \Omega \]

Therefore if \( \Delta i_L = 1 \text{ mA} \), then \( \Delta v_o = -(4.95) \Delta i_L = -4.95 \text{ mV} \)
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.

**Q:** So, is the power delivered by the source *equal* to the power absorbed by 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 $R$. 
The power delivered by the source is:

\[ P_{in} = V_s i = V_s \left( V_s - V_{ZK} \right) / R \]

while the power absorbed by the load is:

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

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:

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

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:

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

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

$$P_{L \text{ max}} = \frac{V_{ZK} (V_s - V_{ZK})}{R}$$

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

$$R_{L \text{ min}} = \frac{V_{ZK} R}{V_s - V_{ZK}}$$
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 \( P_{\text{in}} \):

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

Q: Wait! It appears that the input power is independent of the load resistance \( R_L \)! Doesn’t that mean that \( P_{\text{in}} \) 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:

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

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

For a shunt regulator, this efficiency is:

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

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 \( P_L = P_L^{\text{max}} \).
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 \( P_L^{\text{max}} \).
Voltage Regulators

Note that we can view a shunt regulator as a three-terminal device, inserted between a voltage source and a load:

Integrated circuit technology has resulted in the creation of other three terminal voltage regulator designs—regulators that do not necessarily use zener diodes!
These integrated circuit voltage regulators are small and relatively inexpensive.

In addition, these IC regulators typically have better load regulation, line regulation, and/or efficiency than the zener diode shunt regulator!

Q: Wow! The designers of these IC regulators obviously had a much better electronics professor than the dope we got stuck with! With what device did they replace the zener diode?

A: The electronic design engineers did not simply "replace" a zener diode with another component. Instead, they replaced the entire shunt regulator design with a complex circuit requiring many transistor components.
Integrated circuit technology then allows this complex circuit to be manufactured in a very small space and at very small cost!