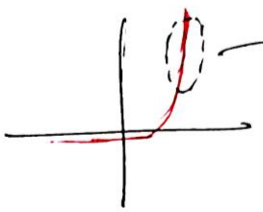
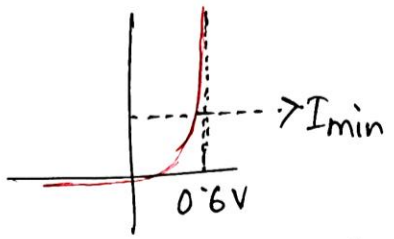
例 Applications :

2. Voltage Regulation :



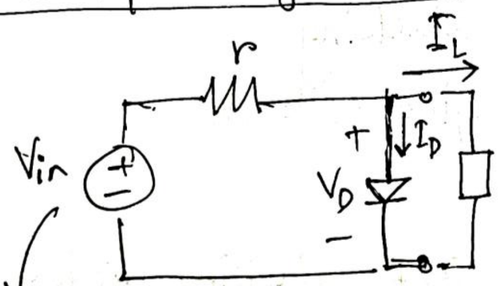
→ looks like the I-V of a voltage-source.

We can use the forward-drop of a non-ideal diode to give a constant voltage at the output.



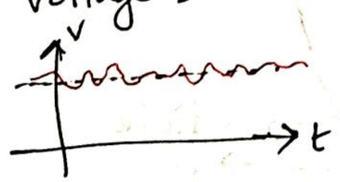
However, the vertical I-V is maintained only if the diode-current is greater than I_{min}.

Example regulator :



→ load resistance

unregulated voltage source



↳ voltage is not perfect DC
- has ripples/ fluctuation

例 Design problem:

$V_{in} = 3V \pm 0.1V$

$I_{min} = 1mA$

Load can draw max^m 10 mA current

What will be r for worst-case?
if V_D is to be regulated at 0.6 V?

For worst case,

Load current is max^m, i.e, $I_L = 10mA$

Diode " " min^m, i.e, $I_D = I_{min} = 1mA$

Input voltage " " , i.e, $V_{in} = 3V - 0.1V = 2.9V$

∴ To maintain regulation at worst-case,

$$\frac{V_{in}(min) - 0.6}{r} = I_L + I_D$$

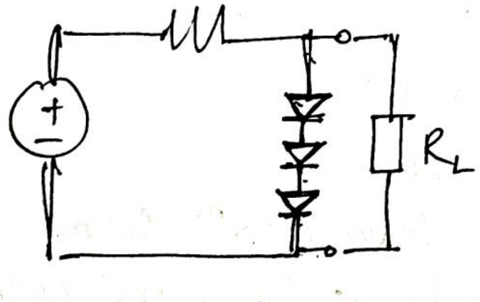
$$\Rightarrow r = \frac{(2.9 - 0.6)V}{10mA + 1mA}$$

$$\cong 209\Omega$$

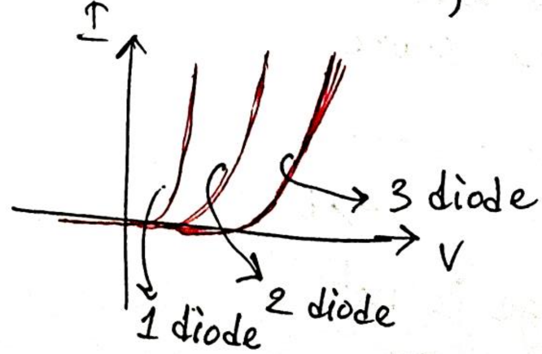
Drawbacks of regulator

1. Regulation voltage is low (only 0.6V !!)
2. I_{min} is relatively high
3. r can become low, and, cause high power loss.

- First drawback can be avoided by stacking diodes in series. 3 diodes can give voltage close to 2 Volts.



But, stacking diodes can lead to a flatter I-V.



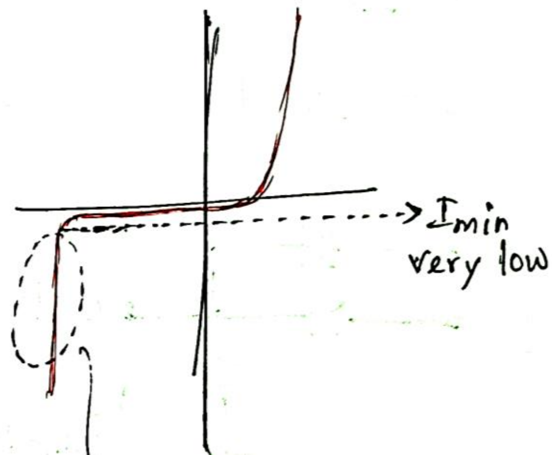
★ So, we usually don't stack more than 3 diodes.

- Better solⁿ ???

⇒ Use the reverse-breakdown region of the diode I-V.

Pros

1. Breakdown voltage can be controlled during fabrication.
2. I_{min} for reverse-breakdown can be very low.



I-V is very vertical during breakdown.
Very good voltage source!! (😃)

Diodes which are designed/fabricated to operate <u>reliably</u> in breakdown are Zener Diodes.

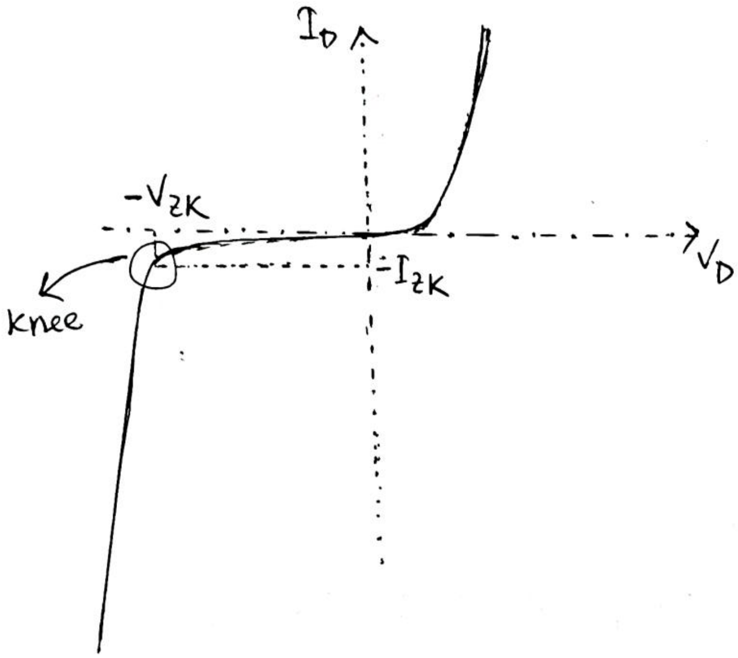
Symbol: 

Practice Problem:

Design a voltage regulator using a 2V - Zener Diode with the constraints of the previous problem.
Find the value of r in this case.

Voltage Regulators with Non-Ideal Zeners

Previously, we assumed that, the IV of a zener-diode is completely vertical in breakdown. However, for a real zener diode in breakdown, there is some slope in the IV.



So, during reverse breakdown, a *real* zener-diode may be modelled as a voltage source with a series resistance.

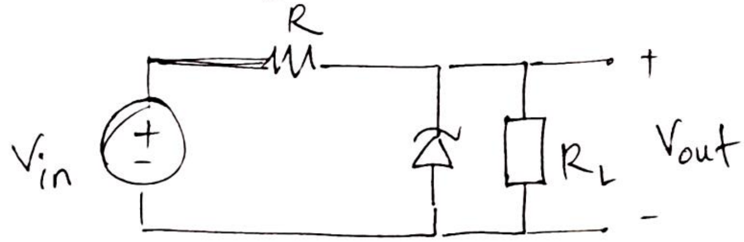
The minimum point upto which the zener can stay in breakdown is called the knee. The voltage and current at that point are the Knee-Voltage (V_{ZK}) and Knee-Current (I_{ZK}).

To stay in break-down, the reverse zener current must be at least, or, more than the knee-current.

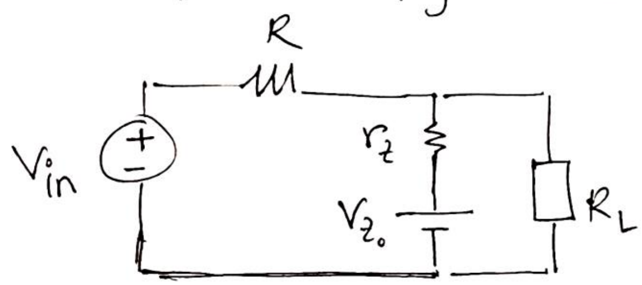
* In spite of having a slope in break-down, the IV is almost vertical. So, the series resistance is very small. Usually, it is in the range $10\Omega \sim 50\Omega$.

Characteristics of a Non-ideal Voltage Regulator :

Our basic regulator ckt is this :



When considering a reverse IV with a slope, we can replace it with a Voltage Source and Series resistance.



[Note that... $V_{z_0} \neq V_{ZK}$. Although, they are pretty close.].

For a regulator like this, the output voltage <u>doesn't</u> stay constant if the <u>Input Voltage</u> or the <u>Output Current</u> changes. V_{out} changes. We want to quantify this change.

2 measures of this change are:

(1) Line Regulation :

This is the change in output voltage with respect to the change in <u>line voltage</u> (i.e, Input Voltage) — keeping load resistance fixed.

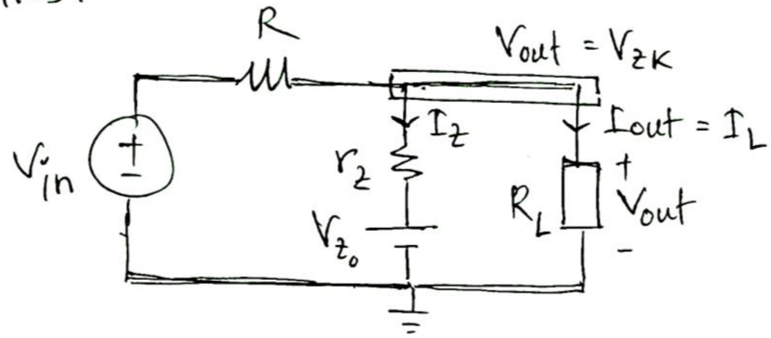
Mathematically, line regulation = $\dfrac{d V_{out}}{d V_{in}}$.

(2) Load Regulation :

This is the change in output voltage w.r.t. load current (i.e, output current.) — keeping input voltage fixed.

Mathematically, load regulation = $\dfrac{dV_{out}}{dI_{out}}$

For our basic Voltage regulator, we will find these 2 quantities.



As before we will proceed from the node equation of V_{out}.

$$\frac{V_{out}-V_{in}}{R} + I_z + I_L = 0 \;\Rightarrow\; \frac{V_{out}-V_{in}}{R} + \frac{V_{out}-V_{z_0}}{r_z} + I_{out} = 0 \quad \text{—— (1)}$$

For line-regulation, $I_{out} = \dfrac{V_{out}}{R_L}$.

$$\therefore \frac{V_{out}-V_{in}}{R} + \frac{V_{out}-V_{z_0}}{r_z} + \frac{V_{out}}{R_L} = 0.$$

$$\Rightarrow V_{out}\left(\frac{1}{R}+\frac{1}{r_z}+\frac{1}{R_L}\right) = \frac{1}{R}V_{in} + \frac{1}{r_z}V_{z_0}$$

$$\therefore V_{out} = \frac{R\|r_z\|R_L}{R}\cdot V_{in} + \frac{R\|r_z\|R_L}{r_z}\cdot V_{z_0} \quad \text{—— (11)}.$$

Here, $R_p = R\|r_z\|R_L$ is the parallel combination of R, r_z and R_L.

i.e, $\dfrac{1}{R_p} = \dfrac{1}{R} + \dfrac{1}{r_z} + \dfrac{1}{R_L}$

$\therefore$ From (11), $\dfrac{dV_{out}}{dV_{in}} = \dfrac{R\|r_z\|R_L}{R}$ [Line Regulation] —— (3)

As a special case, if no load is connected to the output. (i.e, if output is open-circuited or $R_L = \infty$)

$$\frac{dV_{out}}{dV_{in}} = \frac{R \| r_z}{R} = \frac{r_z}{r_z + R} \quad \text{———} (\ )$$

For load-regulation, we can start directly from eqⁿ (1),

$$\frac{V_{out} - V_{in}}{R} + \frac{V_{out} - V_{z_0}}{r_z} + I_{out} = 0 .$$

$$\Rightarrow V_{out}\left(\frac{1}{R} + \frac{1}{r_z}\right) = -I_{out} + \frac{1}{R} V_{in} + \frac{1}{r_z} V_{z_0}$$

$$\therefore V_{out} = -(R \| r_z) \cdot I_{out} + \frac{R \| r_z}{R} V_{in} + \frac{R \| r_z}{r_z} V_{z_0}$$

As before, $R_p = R \| r_z$ is the parallel combⁿ of R and r_z.

i.e, $\frac{1}{R_p} = \frac{1}{R} + \frac{1}{r_z}$.

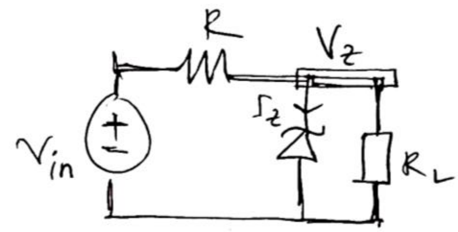
$$\therefore \frac{dV_{out}}{dI_{out}} = -R \| r_z = -\frac{R \cdot r_z}{R + r_z} \quad \text{[Load Regulation]} \text{———} (4)$$

In both cases, eqⁿ (3) and (4), the regulation decreases with r_z. For a zener with completely vertical IV, $r_z = 0$, and, both $\frac{dV_{out}}{dV_{in}}$ and $\frac{dV_{out}}{dI_{out}}$ will be equal to 0.

Finding corner parameters with r_z:

To find the corner values of different parameters of voltage regulator [$V_{in}(min)$, $I_L(max)$, $R_L(min)$, $R(max)$], we use the following node-equation:

$$\frac{V_z - V_{in}}{R} + I_z + I_L = 0$$



To find the corner values, we always have to set,

$$V_z = V_{ZK} \text{ and } I_z = I_{ZK}.$$

If one of them is not given, they have to be inferred from other data.

E.g, if V_{z_0}, r_z and I_{ZK} are given, we can find V_{ZK} using,

$$V_{ZK} = V_{z_0} + I_{ZK} \cdot r_z$$

Example:

You are a circuit-engineer who has to design a voltage regulator. The zener diodes you ~~have~~ own have a knee current of 1mA, a series resistance of 25Ω and $V_{z_0} = 4V$.

The customer to which you will sell the regulator has a supply of 6V with $\pm 0.2V$ ripple. ~~the~~ The lowest resistance that he will connect to the output of the regulator is $0.5k\Omega$.

Find the value of R such that the regulator will work properly in the worst-case condition.

Here, we will use the ~~true~~ worst-case values for all parameters.

~~I_{ZK}~~ $I_Z = I_{ZK} = 1\,mA$

$$V_Z = V_{ZK} = V_{Z_0} + I_{ZK} \times r_Z$$
$$= 4 + 1 \times 0.025 \qquad [r_Z = 25\Omega = 0.025\,k\Omega]$$
$$= 4.025\,V$$

[Note: If V_{ZK} was given directly in the question, we wouldn't have to do this step].

$$I_L = I_L(max) = \frac{V_Z}{R_L(min)} = \frac{V_{ZK}}{R_L(min)} = \frac{4.025}{0.5} = 8.05\,mA$$

$$V_{in} = V_{in}(min) = 6V - 0.2V = 5.8V.$$

Plugging all these values in the eq^n —

$$\frac{V_Z - V_{in}}{R} + I_Z + I_L = 0.$$

We get, $R(max) \approx 0.196\,k\Omega \approx 200\Omega$.

** If V_{ZK}, V_{Z_0} and r_Z are given, we can calculate I_{ZK} from that.

** If both V_{Z_0} and r_Z are not given, only the zener breakdown voltage is given, we can use $V_{ZK} = V_Z$ (breakdown).

** If none of V_{Z_0}, r_Z, I_{ZK} are given, we can use $I_{ZK} = 0$.