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XMUT204 Electronic Design

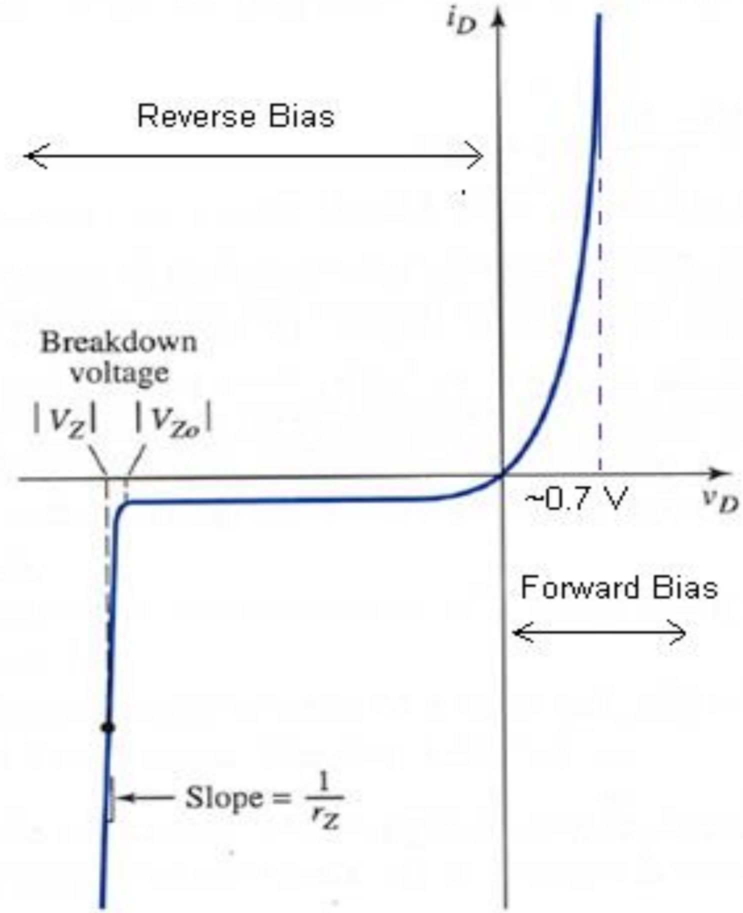
Lecture 2d – Special Purpose Diodes (Zener Diodes)

Overview

1. Zener Diode.
2. Zener Diode Circuit (1N746A).
3. Reverse Bias of Zener Diode.
4. Zener Diode Circuit (1N4740A).
5. Voltage Regulator and Power Supply.
6. Voltage Regulator with Zener Diode.
7. Zener Limiters.
8. Voltage Regulator IC.

Zener Diode

- A special junction diode.
- Controlled breakdown at specified voltage in reverse bias.
- Use this specified voltage (V_Z) as a (relatively) stable voltage reference.
- Its potential uses are as voltage regulator and voltage reference.
- Be aware of limitations of use of Zener diode before you use it in the circuit.



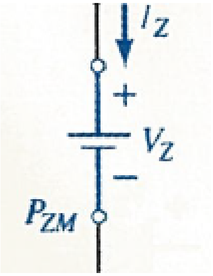
- Consider reverse bias behaviour of a diode:

  a. In the forward bias: it behaves as normal diode with switch on voltage drop at ~0.7 Volt (for silicon diode).

  b. In reverse bias: if $V_d < 0$ but, $V_d > V_z$, the Zener diode is off. It acts as a normal reverse biased diode. No (very small) current flows.

  c. When $V_d << V_z$ (more negative), Zener diode will switch on (breakdown occurs) and the voltage V_d will remain at $\sim V_z$.

- Model of ideal Zener diode in a reverse bias is shown as:



Example for Tutorial 1 – Characteristics of Zener Diode

1. Describe three differences between Zener diode compared with conventional diode. [3 marks]

Answer

Three differences between Zener diode vs. conventional diode are:

- Operated in the reversed bias mode: by design, Zener diode is designed to work in the reversed bias mode in which its anode is connected to the negative side of the voltage source and the cathode must be connected to positive side.

- Slope is steeper than conventional diode's slope: at reverse bias, the rate of change of the current against rate of change of the Zener diode is more pronounced than conventional diode.

- Zener diode does not suffer from an avalanche breakdown, but a slightly different kind of breakdown which is called the Zener breakdown.

2. A Zener diode has an impedance of 5 Ω. What is its terminal voltage at 50 mA if $V_Z = 4.7$ V at $I_Z = 25$ mA? [2.5 marks]

Answer:

The impedance of the Zener diode is calculated from:

$$Z_z = \frac{\Delta V_Z}{\Delta I_Z} = \frac{V_{z2} - V_{z1}}{I_{z2} - I_{z1}}$$

Rearranging the equation given above, the terminal voltage is:

$$V_{z2} = Z_z \times (I_{z2} - I_{z1}) + V_{z1}$$
$$= 5 \times (50 \text{ mA} - 25 \text{ mA}) + 4.7 = 4.825 \text{ V}$$

Example for Tutorial 2 - Zener Diode Circuit (1N746A)

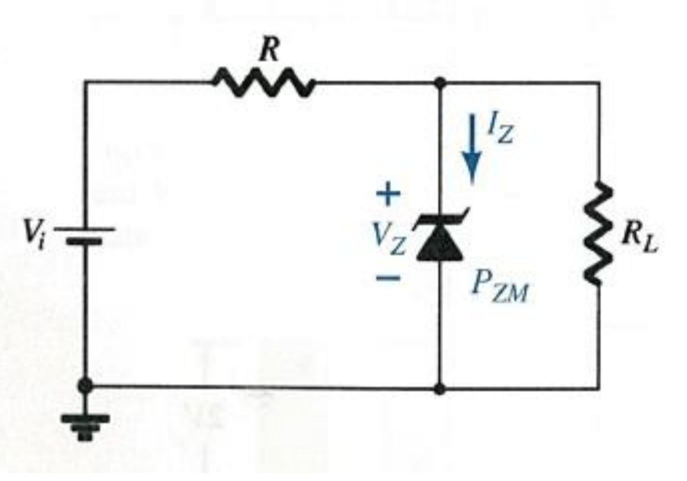
- The following diagram shows a typical circuit with a 1N746A Zener diode.
- In this circuit we have:

  V_i = 5 V,

  R = 330 Ω,

  R_L = 50 Ω, and

  V_Z = 3.3 V.



Electrical Characteristics T_A=25°C unless otherwise noted

Device	V_Z (V) @ I_Z = 20mA (Note 1)			Z_Z (Ω) @ I_Z = 20mA	I_{ZM} (mA) (Note 2)	I_R (μA) @ V_R = 1V	
	Min.	Typ.	Max.			Ta = 25°C	Ta = 125°C
1N4370A	2.28	2.4	2.52	30	150	100	200
1N4371A	2.57	2.7	2.84	30	135	75	150
1N4372A	2.85	3.0	3.15	29	120	50	100
1N746A	3.14	3.3	3.47	28	110	10	30
1N747A	3.42	3.6	3.78	24	100	10	30

a. How do we know if Zener is on? [4 marks]

b. Change value of the load resistor (50 Ω to 1 kΩ). Is Zener diode on? Calculate all voltages and currents in the circuit. [24 marks]

c. Determine the power ratings of the devices e.g. Zener diode and resistor. [6 marks]

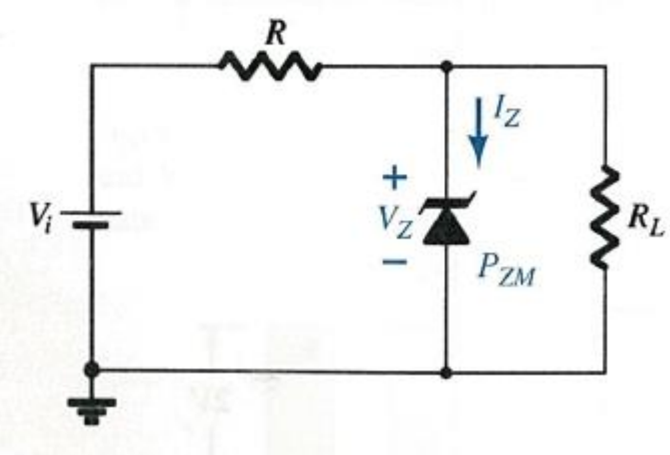
d. Determine power rating of the Zener diode (operated at 50°C). [4 marks]

e. Increase again the value of load resistance (1 kΩ to 10 kΩ). Is Zener diode on? Calculate all voltages and currents in the circuit. [24 marks]

a. How do we know if Zener is on?

- For the given circuit:

Voltage over diode (V_d) = Voltage over load resistor (V_{R_L})



- Remove diode from the circuit (open circuit) and calculate V_{R_L} (e.g. voltage divider circuit):

$$V_{R_L} = \left(\frac{R_L}{R + R_L}\right) V_i$$

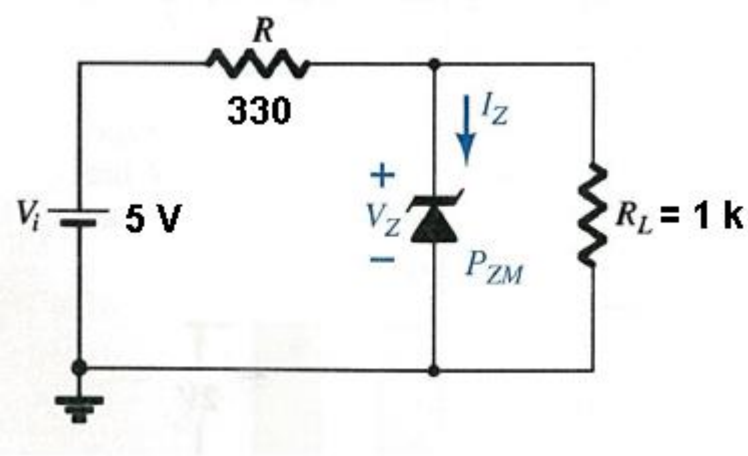
- Taking the values of the components in the circuit:

$$V_{R_L} = \left(\frac{50\ \Omega}{330\ \Omega + 50\ \Omega}\right) \times 5\ \text{V} = 0.66\ \text{V}$$

- As a result $V_{R_L} = V_d = 0.66\ \text{V}$ which will not be enough to turn a Zener diode (V_z = 3.3 V).
- This will act as if Zener diode does not exist in the circuit.

b. Change value of load resistor (50 Ω to 1 kΩ). Is diode on? Calculate all voltages and currents in the circuit.

- If we change the load resistor from 50 Ω to 1 kΩ, then the circuit becomes:



- The voltage across the load resistor:

$$V_{R_L} = \left(\frac{1\ \text{k}\Omega}{1\ \text{k}\Omega + 330\ \Omega}\right) \times 5\ \text{V} = 3.75\ \text{V}$$

- As $V_{R_L} = V_d = 3.75$ V, this $V_d > V_Z$ (for 1N746A Zener diode, V_Z = 3.3 V) -> Zener diode is on.

- If the diode is on, voltage across the diode:

$$V_d = V_z = V_{R_L} = 3.3 \text{ V}.$$

- Voltage drop across the resistor R.

$$V_R = 5 \text{ V} - 3.3 \text{ V} = 1.7 \text{ V}$$

- Two resistors (e.g. R and R_L) are not voltage divider anymore.
- Current that flows in the resistor is:

$$I_R = \frac{V_R}{R} = \frac{1.7 \text{ V}}{330 \ \Omega} = 5.15 \text{ mA}$$

- This current will divide into two:

  a. A current through the load (I_{R_L}).

  b. A current through the Zener diode (I_Z).

- Current through load:

$$I_L = \frac{V_L}{R_L} = \frac{3.3\ V}{1\ \mathrm{k\Omega}} = 3.3\ \mathrm{mA}$$

- Current that flows through the Zener diode:

$$I_Z = 5.15\ \mathrm{mA} - 3.3\ \mathrm{mA} = 1.85\ \mathrm{mA}$$

- Power dissipated by resistor R:

$$P_R = V_R I_R = 1.7\ \mathrm{V} \times 5.15\ \mathrm{mA} = 8.8\ \mathrm{mW}$$

- Power dissipated by Zener diode:

$$P_Z = V_Z I_Z = 3.3\ \mathrm{V} \times 1.85\ \mathrm{mA} = 6.1\ \mathrm{mW}$$

c. Determine the power ratings of the devices.

- Choose components that safely dissipate the power.

Absolute Maximum Ratings * T_A = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
P_D	Power Dissipation @ TL ≤ 75°C, Lead Length = 3/8"	500	mW
	Derate above 75°C	4.0	mW/°C
T_J, T_{STG}	Operating and Storage Temperature Range	-65 to +200	°C

* These ratings are limiting values above which the serviceability of the diode may be impaired.

- Assume that the rating of the resistor is using standard resistor power:

$$P_R \text{ (max)} = 0.25 \text{ Watt}$$

- The Zener diode rating is found to be (IN746A):

$$P_Z \text{ (max)} = 500 \text{ mW}$$

- Both power dissipations are well within limits.

d. Determine the power rating of the diode (operated at 50°C).

- The power rating is specified for a specific temperature, or up to a specific temperature.
- From datasheet of IN746A this reads:

$$P_Z\ (\text{max}) = 500\ \text{mW @ 25°C}$$

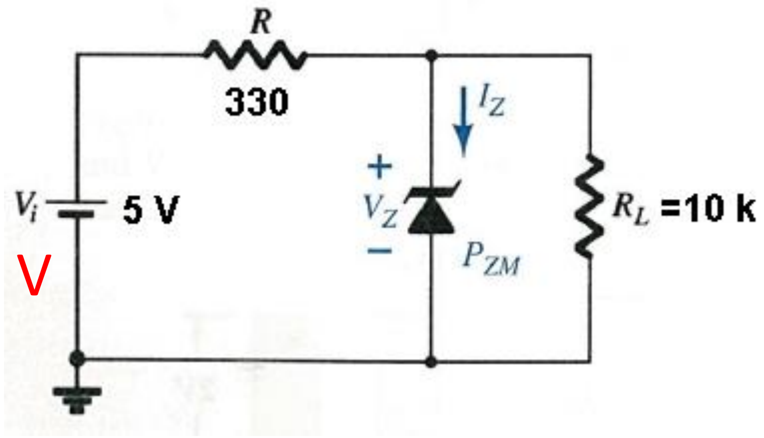
- If this temperature is exceeded, the power should be derated at 3.33 mW/°C (for temperature < 75 °C).
- Expect the device to operate @ 50°C.
- The value for $P_Z\ (\text{max})$ will be:

$$P_Z\ (\text{max}) = 500\ \text{mW} - (50°\text{C} - 25°\text{C}) \times 3.33\ \text{mW/°C}$$

$$= 418\ \text{mW}$$

e. Increase again value of load resistance (1 kΩ to 10 kΩ). Is Zener diode on? Calculate all voltages and currents in circuit.

- Is the Zener diode on?



$$V_{R_L} = \left(\frac{10\ \text{k}\Omega}{10\ \text{k}\Omega + 330\ \Omega}\right) \times 5\ \text{V}$$

$$= 4.84\ \text{V}$$

- Hence, the Zener diode is on (e.g. V_Z = 3.3 V).

- Voltage across the diode is:

$$V_D = V_{R_L} = V_Z = 3.3\ \text{V}$$

- Voltage across the 330 Ω limiting resistor:

$$V_R = 5\ \text{V} - 3.3\ \text{V} = 1.7\ \text{V}$$

- Current in the load resistor, R_L:

$$I_L = \frac{3.3\ \text{V}}{10\ \text{k}\Omega} = 0.33\ \text{mA}$$

- Current in the limiting resistor, R:

$$I_R = (5 - 3.3)/330 = 5.15\ \text{mA}$$

- Current through the Zener diode is:

$$I_Z = 5.15\ \text{mA} - 0.33\ \text{mA} = 4.82\ \text{mA}$$

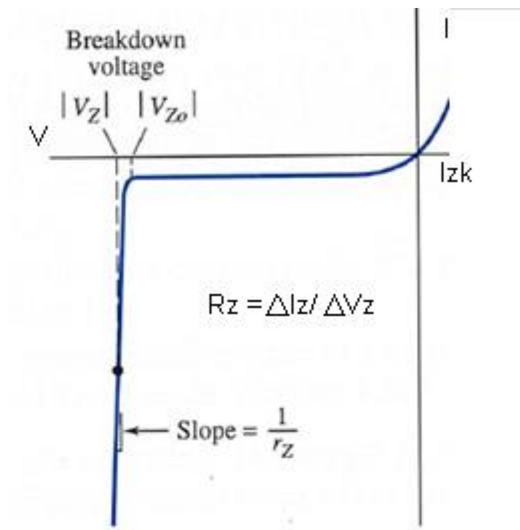
- Power that is dissipated in Zener diode is:

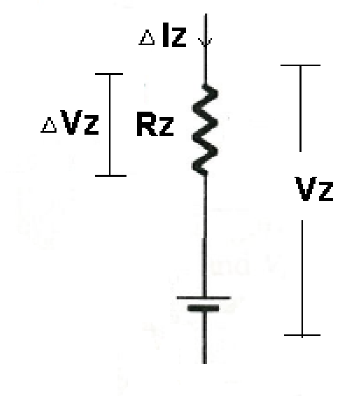
$$P_Z = V_Z I_Z = 3.3\ \text{V} \times 4.82\ \text{mA} = 15.9\ \text{mW}$$

- Power dissipation of Zener diode increases as load resistance increases - should not exceed ~ 80% of max power rating.

Reverse Bias of Zener Diode

- Zener diode reverse bias curve -> the slope in the curve indicates a resistance is present.





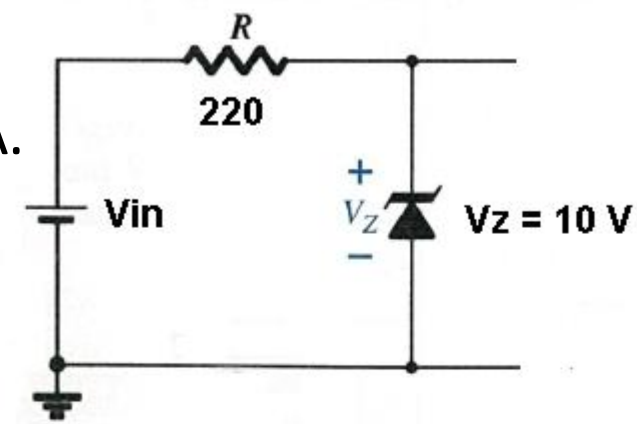
- Better model for Zener diode in reverse bias is:

ideal diode model + voltage source + diode resistance

Example for Tutorial 3 - Zener Diode Circuit (1N4740A)

- For circuit given, the Zener diode is 1N4740A.
- Typical value:

$$\Delta V_Z = 50 \text{ mV} \quad \text{and} \quad \Delta I_Z = 5 \text{ mA.}$$



- Zener diode resistance:

$$R_Z = \frac{\Delta V_Z}{\Delta I_Z} = \frac{50 \text{ mV}}{5 \text{ mA}} = 10\ \Omega$$

- Consider a variable input voltage and evaluate the circuit based on this condition.

a. What is the minimum current in the circuit? [4 marks]

b. What is the maximum current in the circuit? [4 marks]

c. Determine the range of input voltage for Zener diode to turn on. [8 marks]

d. Describe how Zener diode is able to handle variable load. [4 marks]

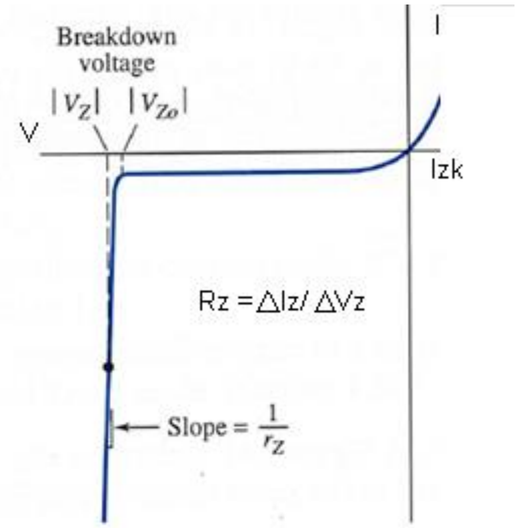
e. What is the minimum load the Zener diode can handle? [12 marks]

a. What is the minimum current in the circuit?

- From datasheet: the lowest current that ensures regulation when the Zener is on (I_{ZK}) i.e. 0.25 mA for 1N4740A.

- This is known as knee current of the Zener diode.

- It is also considered as a no load current.



Electrical Characteristics T_a = 25°C unless otherwise noted

Device	V_Z (V) @ I_Z (Note 1)			Test Current	Max. Zener Impedance			Leakage Current	
	Min.	Typ.	Max.	I_Z (mA)	Z_Z @ I_Z (Ω)	Z_{ZK} @ I_{ZK} (Ω)	I_{ZK} (mA)	I_R (μA)	V_R (V)
1N4738A	7.79	8.2	8.61	31	4.5	700	0.5	10	6
1N4739A	8.645	9.1	9.555	28	5	700	0.5	10	7
1N4740A	9.5	10	10.5	25	7	700	0.25	10	7.6
1N4741A	10.45	11	11.55	23	8	700	0.25	5	8.4
1N4742A	11.4	12	12.6	21	9	700	0.25	5	9.1

b. What is the maximum current in the circuit?

- Calculated from maximum power of Zener diode (as for 1N4740A).
- From the datasheet, max power dissipation is 1 W.
- Maximum current of the Zener diode is:

$$I_Z(\text{max}) = \frac{P_Z(\text{max})}{V_Z} = \frac{1\ \text{W}}{10\ \text{V}} = 100\ \text{mA}$$

Absolute Maximum Ratings * T_a = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
P_D	Power Dissipation @ TL ≤ 50°C, Lead Length = 3/8"	1.0	W
	Derate above 50°C	6.67	mW/°C
T_J, T_{STG}	Operating and Storage Temperature Range	-65 to +200	°C

* These ratings are limiting values above which the serviceability of the diode may be impaired.

c. Determine range of input voltage (minimum and maximum) for Zener diode to turn on.

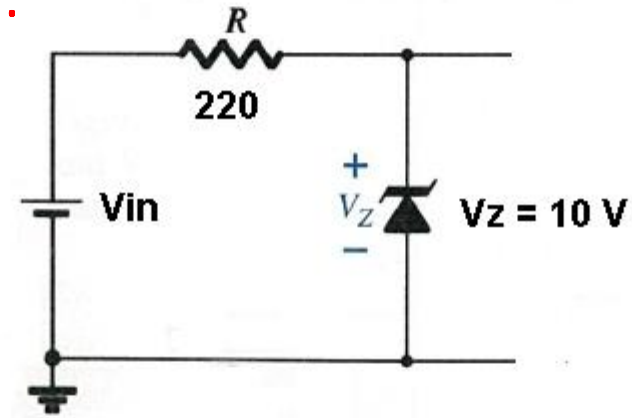
- At no load, all current that flow through R also flows through Zener diode.
- For minimum current through Zener diode (i.e. I_{ZK} = 0.25 mA), voltage drop across the limiting resistor, R is:

$$V_R = (0.25\ \text{mA})(220\ \Omega) = 0.055\ \text{V}$$

- This needs minimum input voltage:

$$V_{in}(\text{min}) = 10\ \text{V} + 0.055\ \text{V}$$

$$= 10.055\ \text{V}$$



- From previous calculation, maximum input voltage is determined by maximum current through Zener diode:

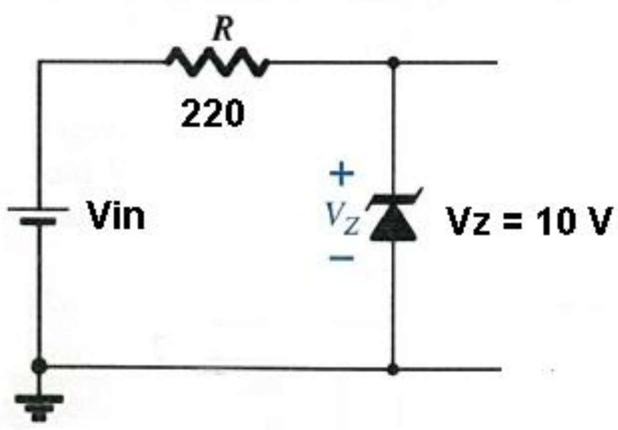
$$I_Z\ (\text{max}) = 100\ \text{mA}$$

- For this current, voltage drop over limiting R is:

$$V_R(\text{max}) = (100\ \text{mA})(220\ \Omega) = 22\ \text{V}$$

- For the maximum input voltage:

$$V_{in}(\text{max}) = V_R(\text{max}) + V_Z = 22\ \text{V} + 10\ \text{V} = 32\ \text{V}$$

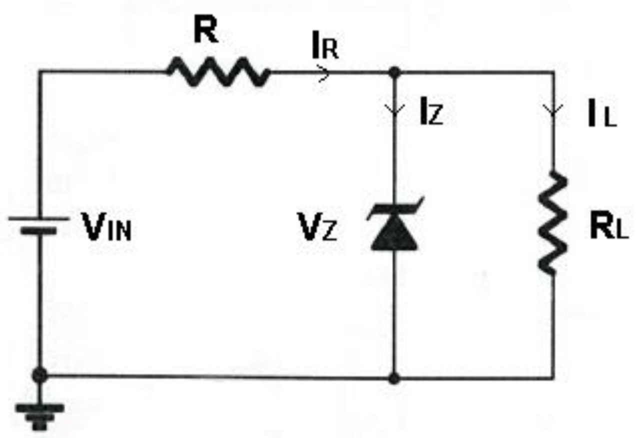


- In practice has safety margins e.g.:

$$V_{in}(\text{min}) + 10\% \qquad V_{in}(\text{max}) - 20\%.$$

- This gives value in the range of 11 ~ 25 V.

d. Describe how Zener diode handles variable load.



- With no load in place ($R_L = \infty$) all current flows through Zener at no load condition.
- When load is connected, current is divided between the one flowing in the Zener diode and in the load.

- The total current remains the same as long as Zener is on:
  a. If R_L is going up, I_L is going down, and I_Z is going up.
  b. If R_L is going down, I_L is going up, and I_Z is going down.
- These limit for I_Z will again determine the values of the load we can use.

Electrical Characteristics T_a = 25°C unless otherwise noted

Device	V_Z (V) @ I_Z (Note 1)			Test Current I_Z (mA)	Max. Zener Impedance			Leakage Current	
	Min.	Typ.	Max.		Z_Z @ I_Z (Ω)	Z_{ZK} @ I_{ZK} (Ω)	I_{ZK} (mA)	I_R (μA)	V_R (V)
1N4738A	7.79	8.2	8.61	31	4.5	700	0.5	10	6
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1N4742A	11.4	12	12.6	21	9	700	0.25	5	9.1

e. What is the minimum load the Zener diode can handle?

- As the load decreases, more current flows in the load and less through Zener diode.

- From the datasheet of the Zener diode, need at least $I_{ZK} = 1\text{ mA}$ in Zener diode for reliable operation.
- Initially ($R_L = \infty$), the current (with $I_L = 0$) at 25.5 mA:

$$I_R = I_Z + I_L = 25.5\text{ mA}$$

- As R_L decreases, I_L increase and I_Z decreases.
- I_Z is minimum when $I_Z = I_{ZK} = 1\text{ mA}$.

Electrical Characteristics $T_a = 25°C$ unless otherwise noted

Device	V_Z (V) @ I_Z (Note 1)			Test Current I_Z (mA)	Max. Zener Impedance			Leakage Current	
	Min.	Typ.	Max.		Z_Z @ I_Z (Ω)	Z_{ZK} @ I_{ZK} (Ω)	I_{ZK} (mA)	I_R (μA)	V_R (V)
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1N4742A	11.4	12	12.6	21	9	700	0.25	5	9.1

- Current flows in the load:

$$I_L = I_R - I_Z = 25.5\text{ mA} - 1\text{ mA} = 24.5\text{ mA}$$

- Resistance across the load (taken at $V_L = 12\text{ V}$):

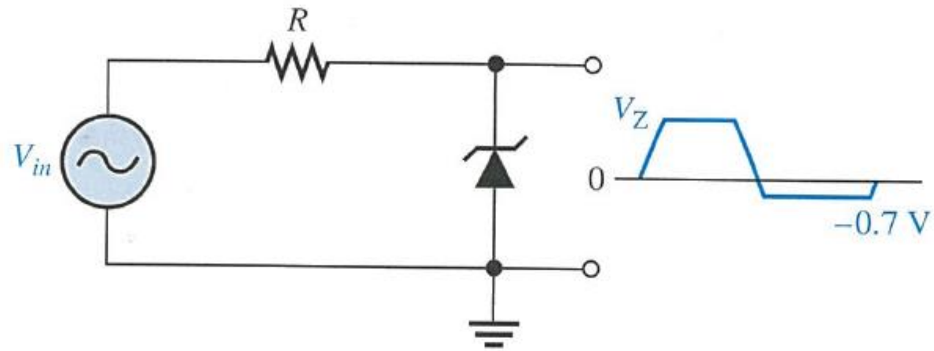
$$R_L = \frac{12\text{ V}}{24.5\text{ mA}} = 490\ \Omega$$

- As calculated above, load resistance can vary between $490\ \Omega \leq R_L \leq \infty$.
- Build in some safety margin on the minimum load resistance ($R_L(\text{min})$):

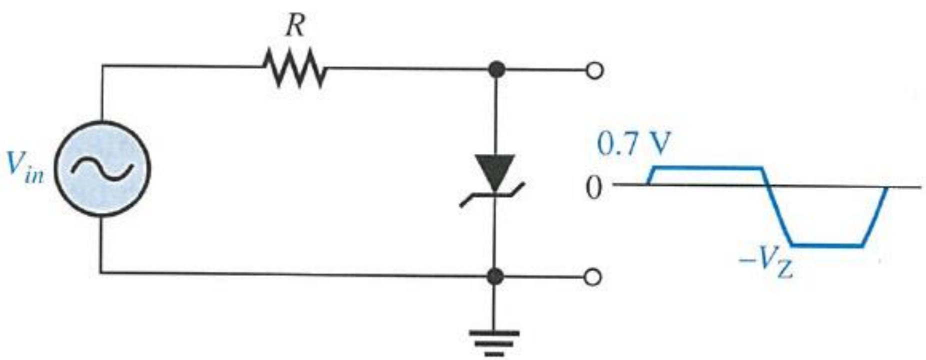
$$R_L(\text{min}) \cong 1\text{ k}\Omega$$

Zener Limiters

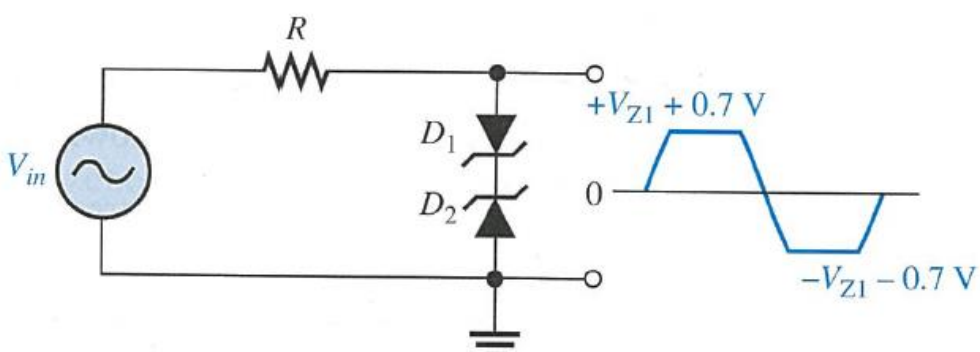
- Circuit configuration of Zener diode as voltage limiters.



$(+V_Z)$ ~ (-0.7) V

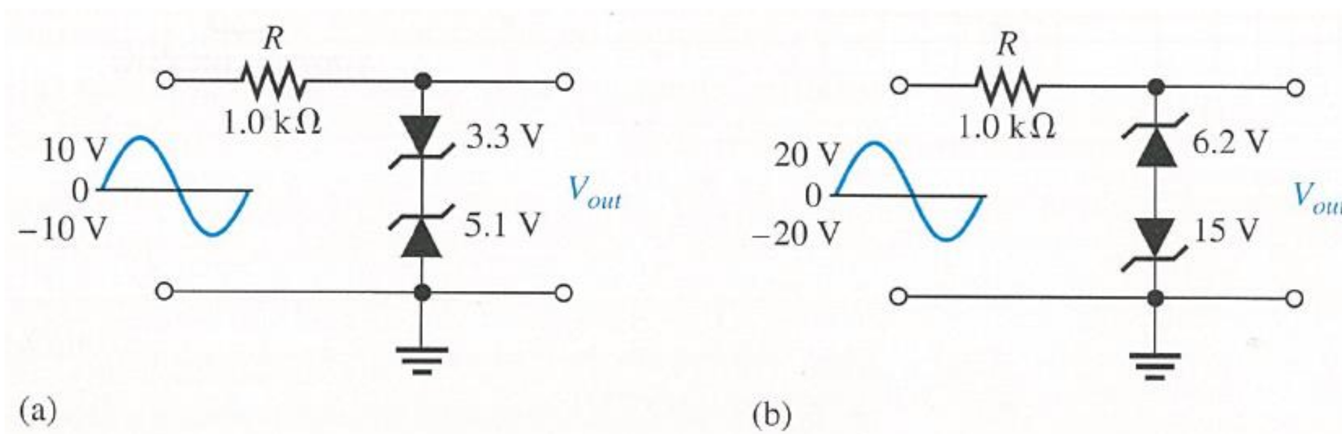


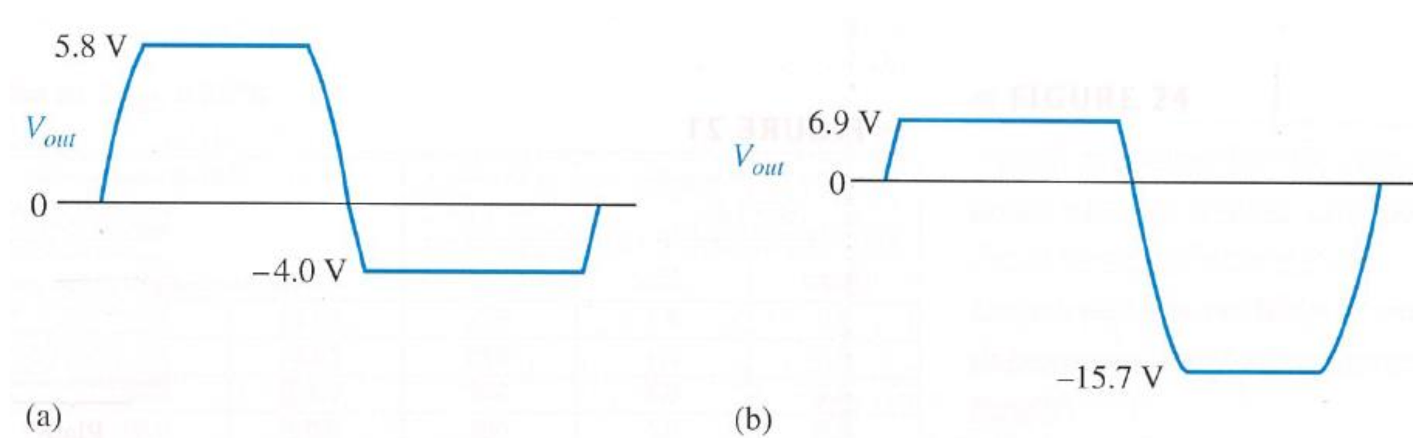
(+0.7) V ~ $(-V_Z)$



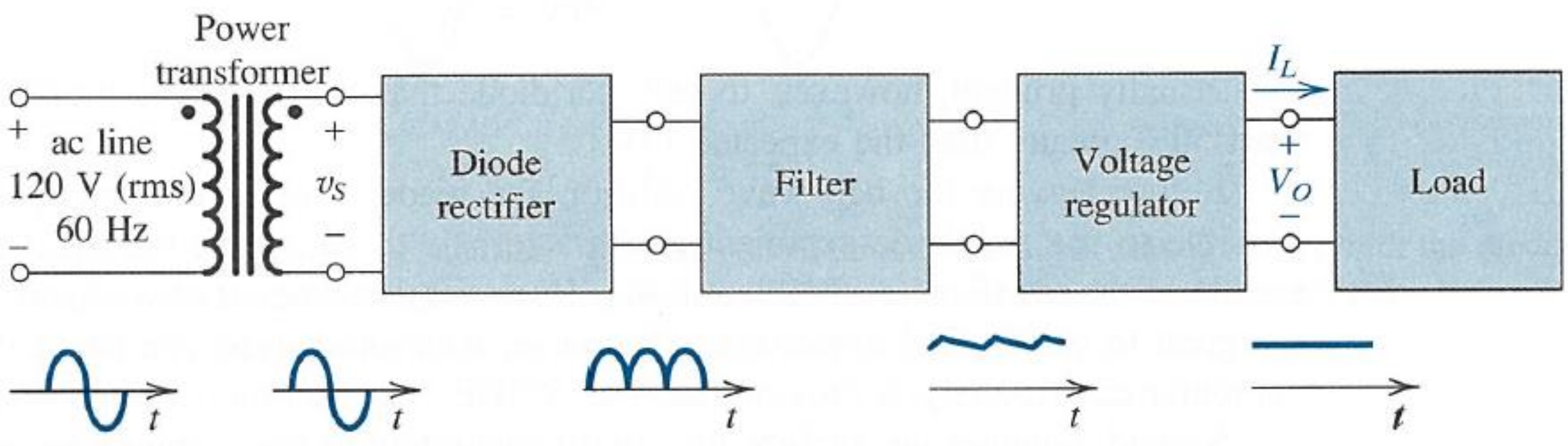
$(+V_Z + 0.7)$ V ~ $(-V_Z - 0.7)$ V

- For the following cases, the thresholds are set at different values than the previous ones.
- Then, what will the following waveforms look like?





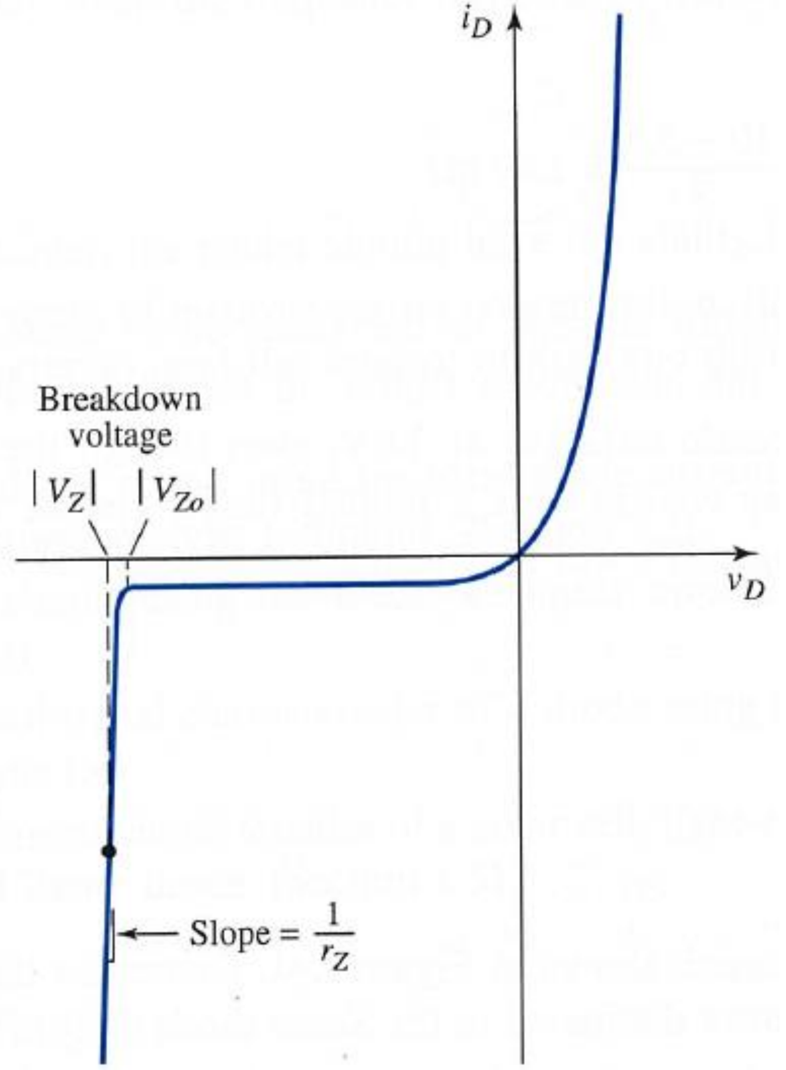
Voltage Regulator with Zener Diode



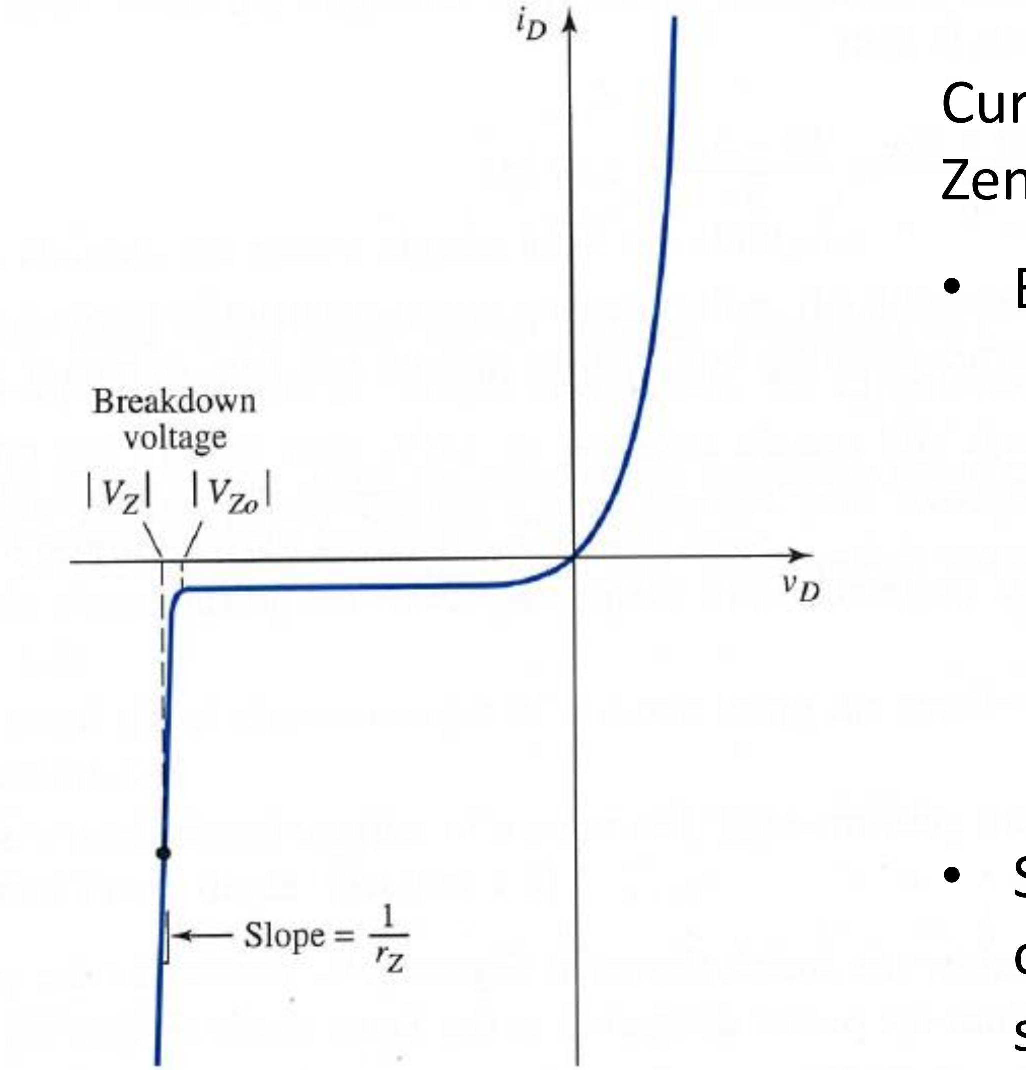
- The last stage in the power supply block diagram ~ a voltage regulation step.
- Keep the output voltage as close as possible to a specified value irrespective of changes in input voltage or load.
- We will now look at different ways to achieve voltage level regulation in a circuit -> Lab 3 is on voltage regulation circuit.

Voltage Regulator with Zener Diode (cont..)

- Zener diodes are designed and fabricated to provide a specified breakdown voltage.
- When used in reverse bias, at breakdown, large currents can flow which needs to be limited to avoid damage to the device.
- It is used as a constant-voltage reference in a circuit, as the breakdown voltage is essentially constant over a range of currents and temperatures.



Voltage Regulator with Zener Diode (cont..)

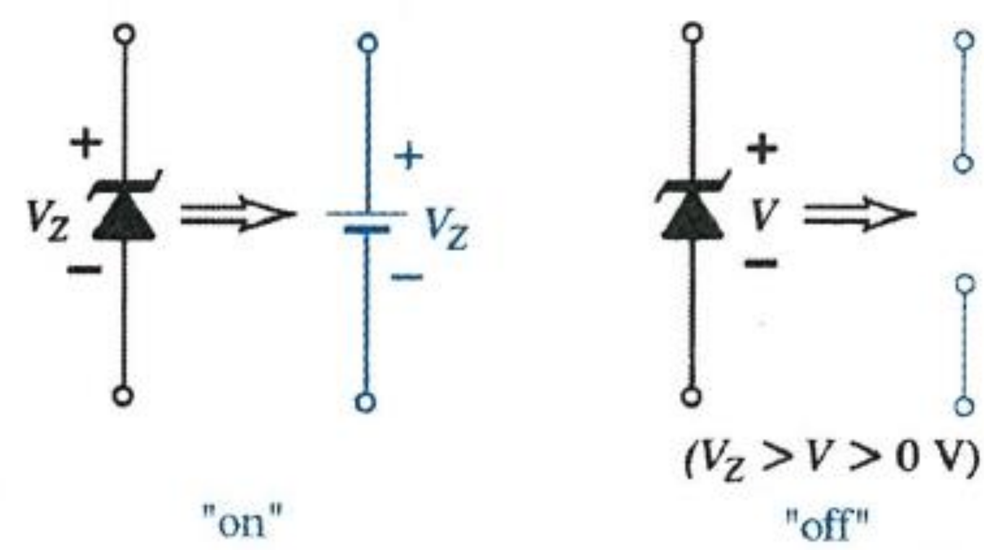


I-V curve for a Zener diode

Current-voltage (I-V) curve for a Zener diode:

- Breakdown voltage:
  - Conventional use ~ 2.4 V to about 200 V.
  - Maximum to 1 kV.
  - Maximum for the SMD is about 47 V.
- Slope: If this is compared with ordinary diode, Zener diode slope is a lot steeper -> exploited for the purpose.

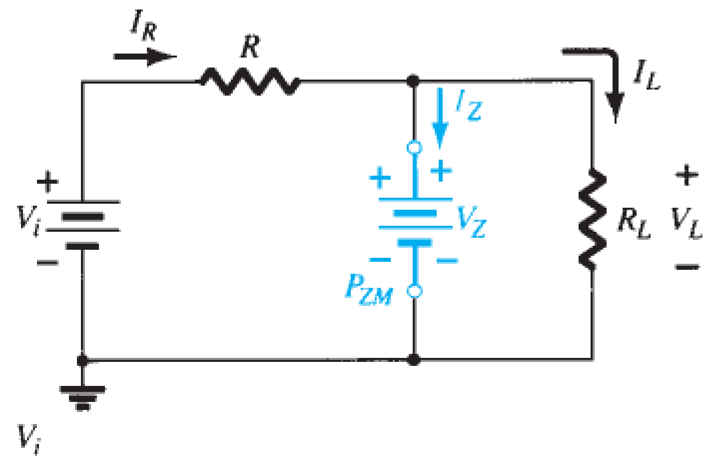
Analysing Zener diode circuits



- If the voltage over the diode is $V_Z > V > 0$, the diode is reverse biased, but below its breakthrough voltage. Diode will thus be OFF and look like a normal reverse biased diode i.e. an open circuit.
- If the diode is reverse biased to its breakthrough voltage, it will have a voltage drop (i.e. the Zener voltage, V_Z) over it. This will also show a very small resistance that can be taken into account in the model.

Analysis of Zener Diode as Voltage Regulator

Consider the Zener circuit given below.

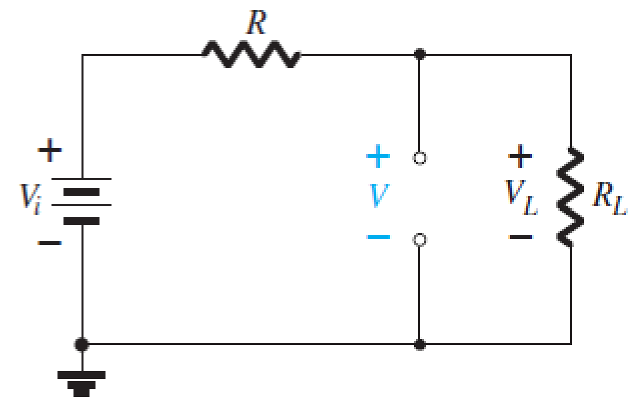


- The applied dc voltage is fixed, as well as the load resistor R_L.
- The analysis can be done in two steps:
  - Diode is ‘OFF’.
  - Diode is ‘ON’.

1. **Determine the state of the Zener diode by removing it from the calculation of the voltage across the open circuit.**

If $V < V_Z$ then the diode is OFF and can be modelled by an open circuit equivalent:

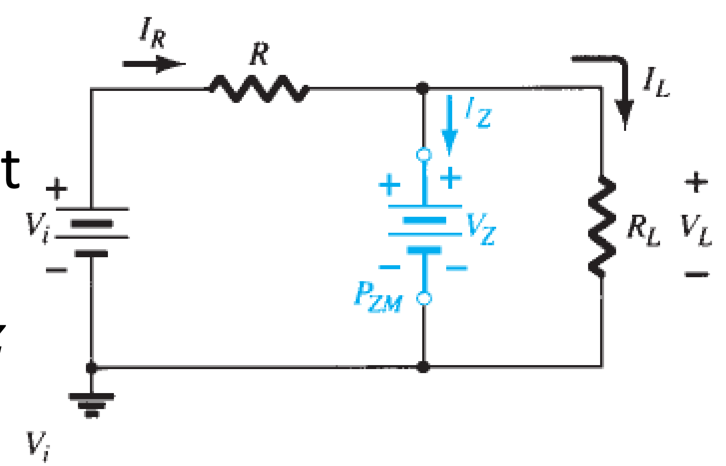
$$V = V_L = V_i\left(\frac{R_L}{R + R_L}\right)$$



2. **Substitute the appropriate equivalent circuit and solve for unknown voltages and currents**

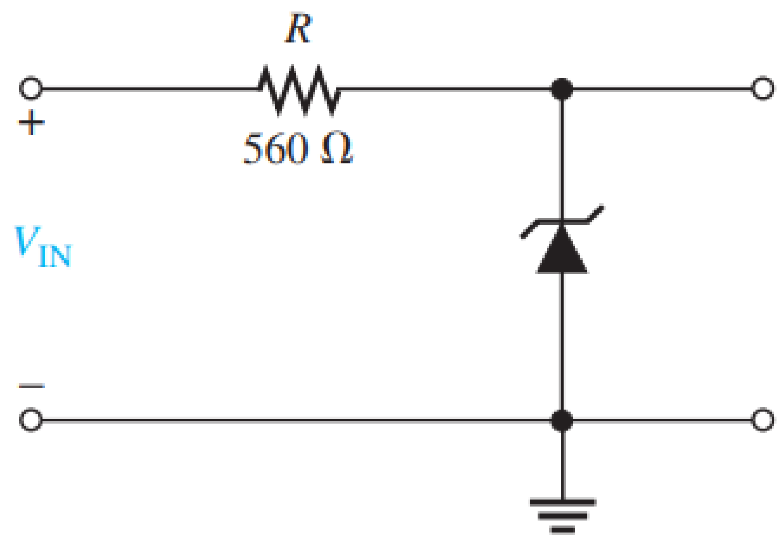
If $V > V_Z$ the diode is ON the equivalent circuit as on right will result. Thus:

$V_L = VZ, I_R = IZ + IL$ and $P_Z = V_Z I_Z$



Example for Tutorial 4 – Zener for Voltage Regulator Circuit

1. If Zener diode is used in a voltage regulation application, assume an ideal Zener diode with minimum current value $(I_{ZK}) =$ 1.5 mA and $V_Z = 14$ V.



a. Describe briefly how Zener diode maintain the voltage in the circuit. [2 marks]

b. Determine minimum input voltage required for regulation to be established in circuit above. [5 marks]

Answer

a. If the voltage across it increases, the Zener diode maintains a constant voltage across the load by absorbing the extra current and keeping the load current constant.

b. For the given Zener diode circuit, applying KVL on the circuit. [2.5]

$$V_{in} = V_R + V_Z = (I_{zk} \times R) + V_Z$$

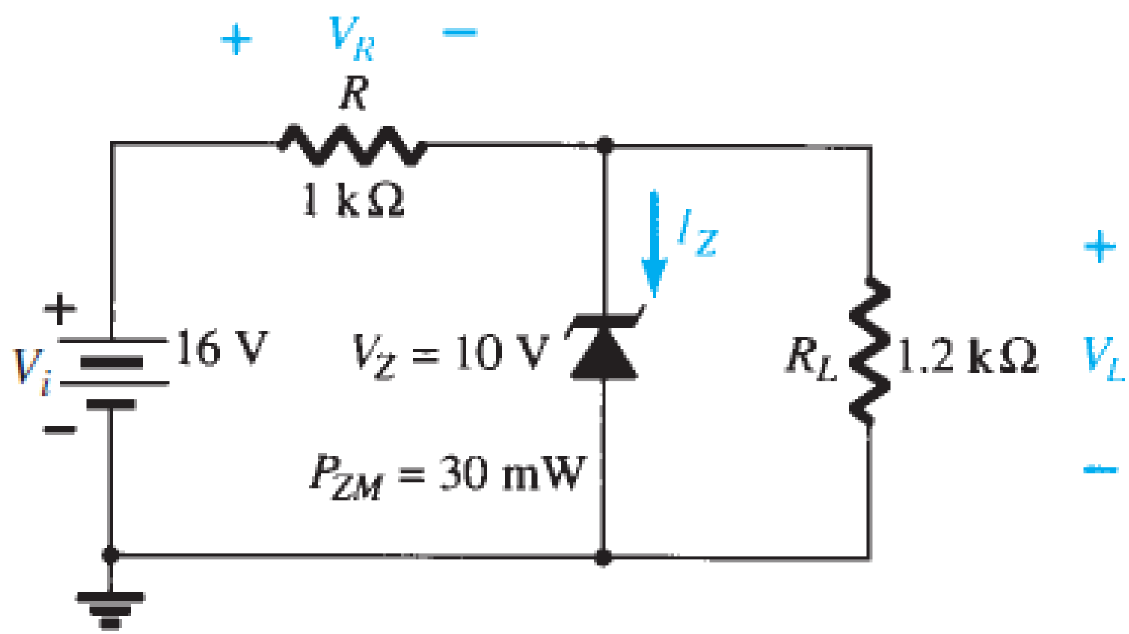
Putting in the values into the equation [2.5]

$$V_{in} = (1.5 \text{ mA} \times 560) + 14 = 14.84 \text{ V}$$

2. For the Zener network as shown below,

a. Calculate V_L, V_R, I_Z and P_Z. [8 marks]

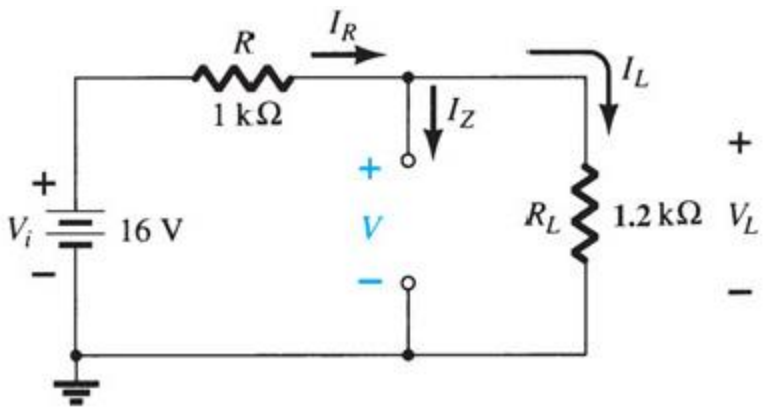
b. Repeat with a load resistor R_L = 3 kΩ. [8 marks]



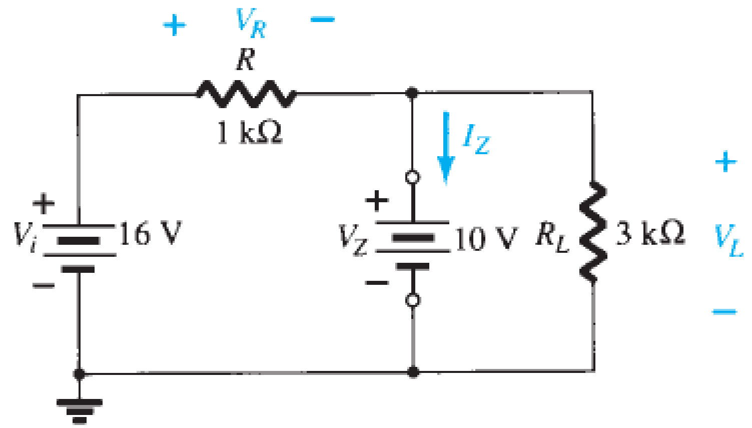
a. Use suggested procedure and remove Zener diode from circuit, calculate for:

$$V_L = 16\left(\frac{1.2\text{k}\Omega}{1\text{k}\Omega + 1.2\text{k}\Omega}\right) = 8.73\text{ V}$$

- Thus, V_L is below the turn on voltage for the Zener diode –> diode OFF.
- Thus, $V_R = V_i - V$ = 16 – 8.73 = 7.27 V and I_Z = 0 and P_Z = 0.



b. Change the load resistor to R_L = 3 kΩ



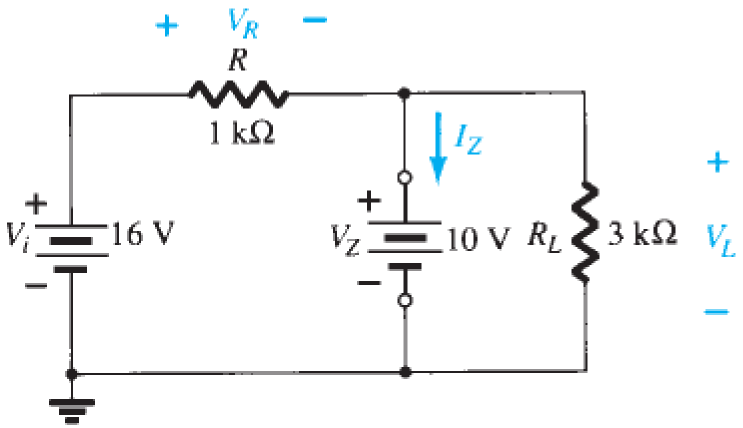
- For the diode “removed”, given:

$$V_L = 16\left(\frac{3\text{k}\Omega}{1\text{k}\Omega + 3\text{k}\Omega}\right) = 12\ \text{V}$$

- For V_L = 12 V, this exceeds turn on of Zener diode -> the diode is ON.
- If the diode is ON, V_Z = V_L = 10 V, so that V_R = 6 V

- Current in the load R_L:

$$I_L = \frac{V_L}{R_L} = \frac{10}{3000} = 3.33 \text{ mA}$$



- Current in the limiting resistor R:

$$I_R = \frac{V_R}{R} = \frac{6}{1000} = 6 \text{ mA}$$

- Thus, current through Zener diode:

$$I_Z = I_R - I_L = 6 \text{ mA} - 3.33 \text{ mA} = 2.67 \text{ mA}$$

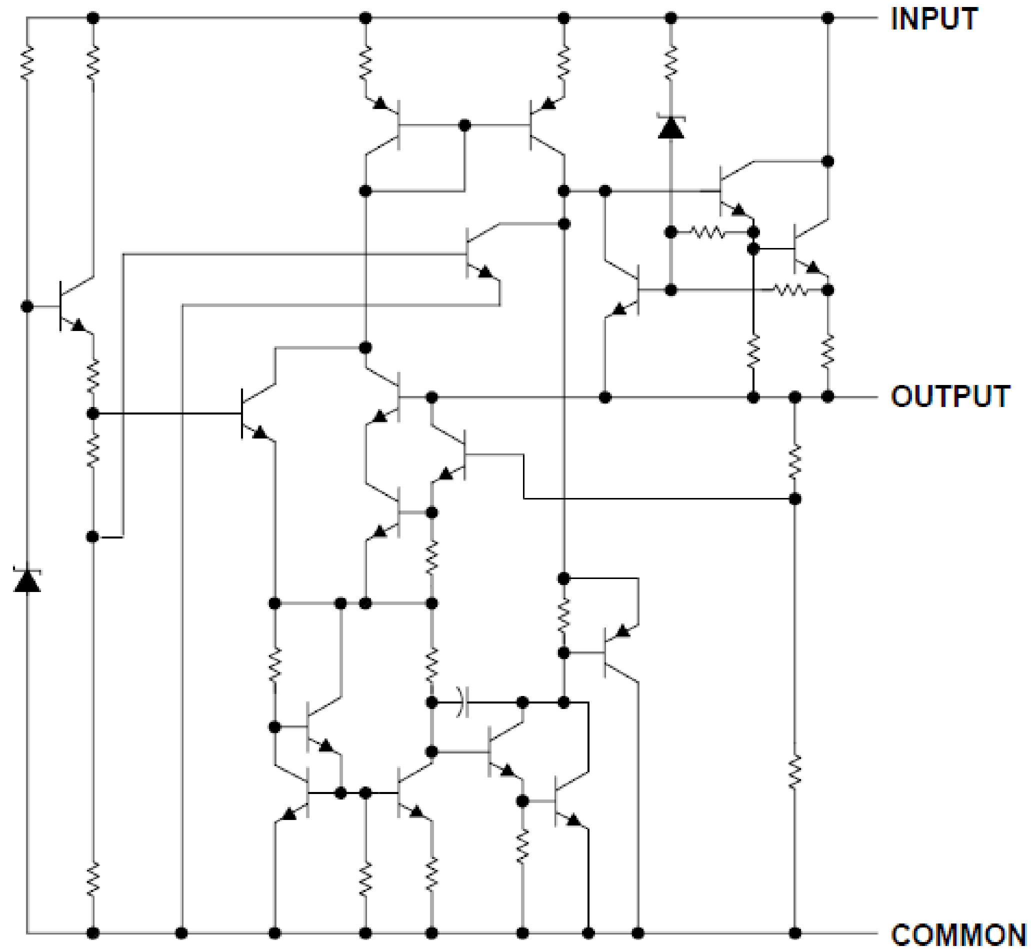
- Power dissipated in the Zener diode:

$$P_Z = (10 \text{ V})(2.67 \text{ mA}) = 26.7 \text{ mW}$$

- As a result, $P_Z < P_{ZM}$ of 30 mW.

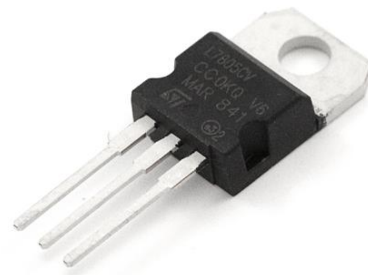
LM7805 Integrated Circuit Voltage Regulator

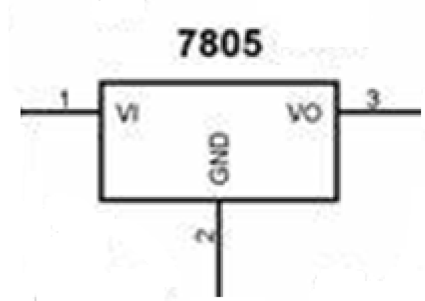
- To end off: real life is always a bit more complicated!
- A real voltage regulator i.e. schematic of the LM7805 (it is a +5 V IC voltage regulator).

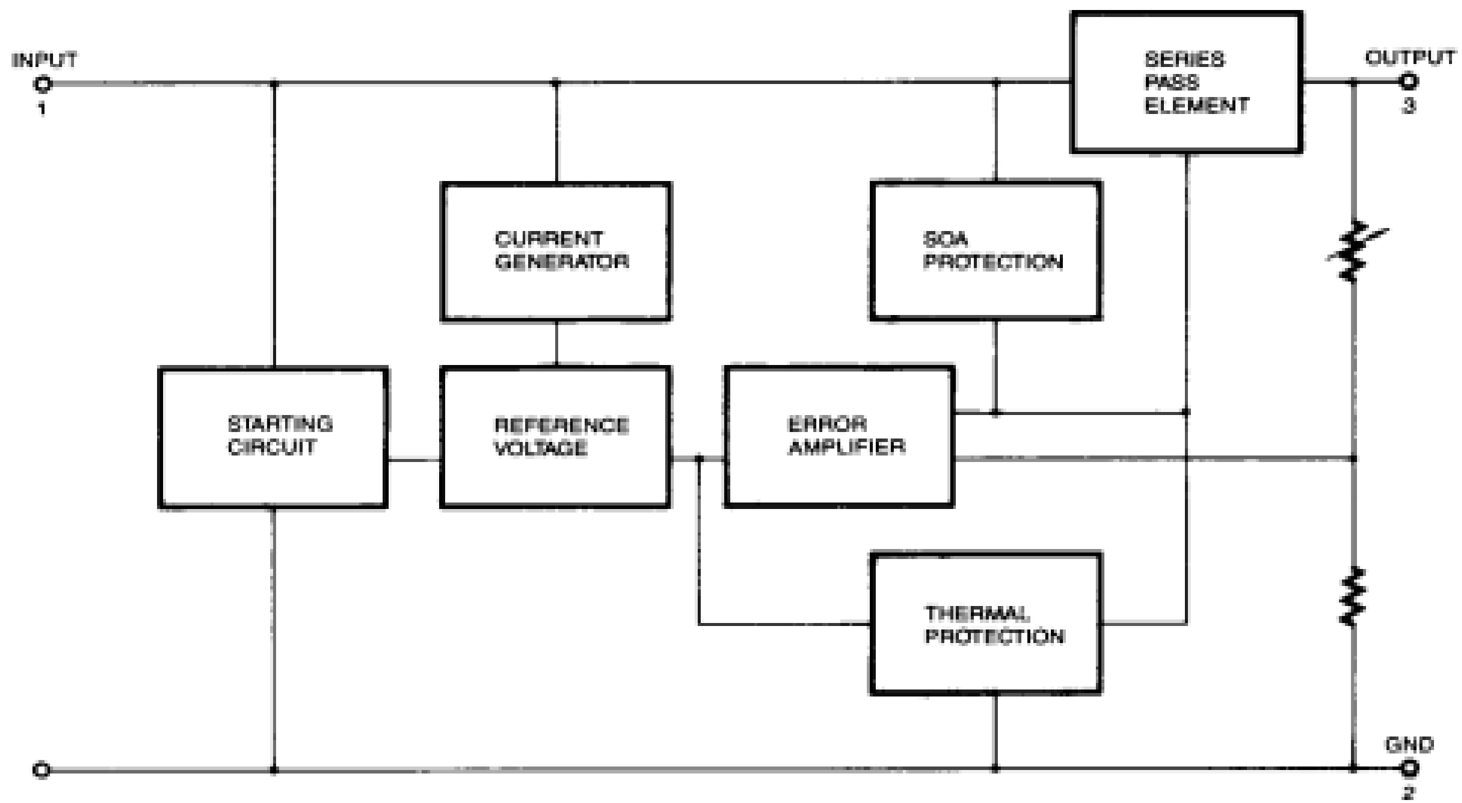


LM7805 Integrated Circuit

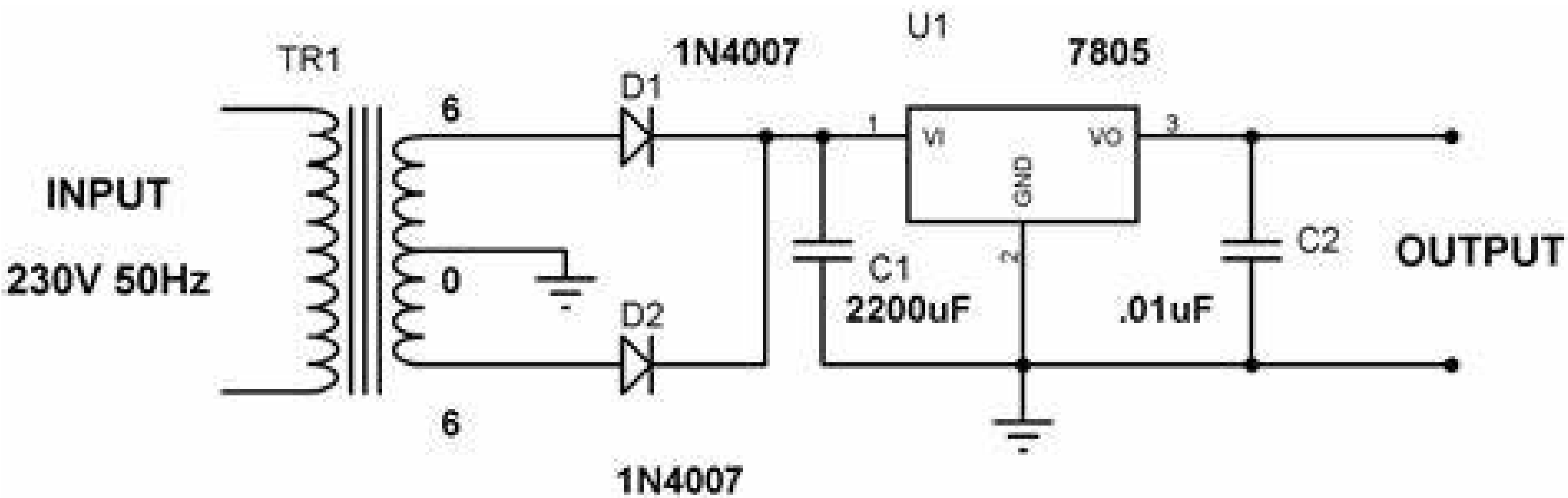
- Internal block diagram of LM7805 voltage regulator IC.







Power Supply based on LM7805



- Step down transformer from 220 V AC to 6 V AC.
- Centre tap full-wave diode rectifier.
- Input capacitor to smooth out ripple in the input.
- A voltage regulator LM7805 provides +5 V DC in the output.
- Output capacitor to smooth out ripple in the output.