ELECTRONIC PRINCIPLES AND DEVICES

Department of Electronics and Communication.

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Unit 2: Diode applications

Department of Electronics and Communication.

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Regulated Power Supply

Power supplies are designed for a dedicated load and environment. But sometimes main supply voltage, load, and surrounding temperature keep changing, altering the component parameters and hence changing the output voltage.

If the power supply output voltage changes, chances are it may cross these current thresholds, which are undesirable for electronic devices that work within power limits.

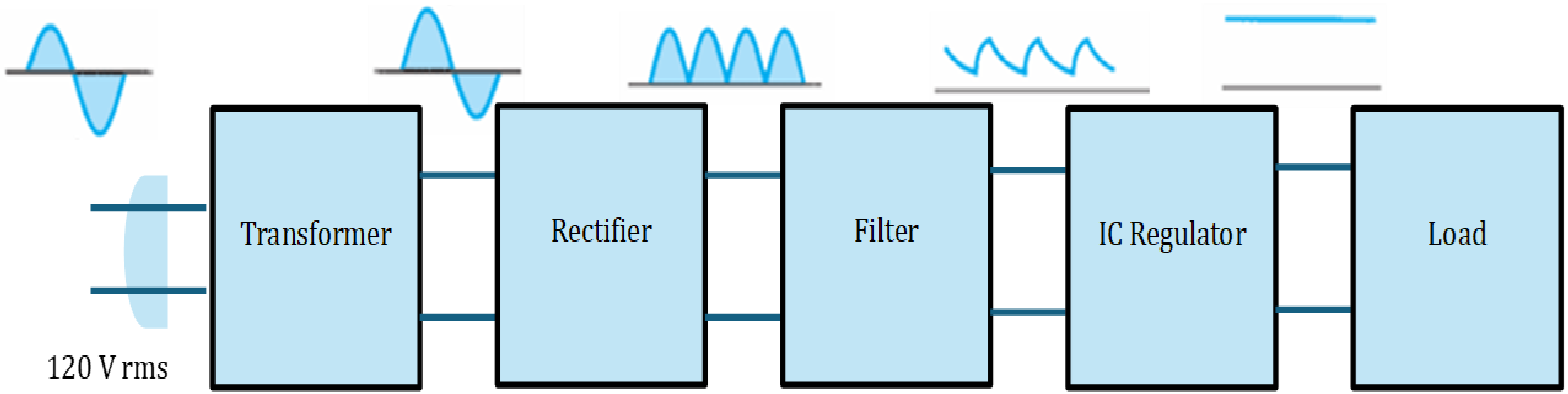


Fig 1: Block diagram of regulated power supply

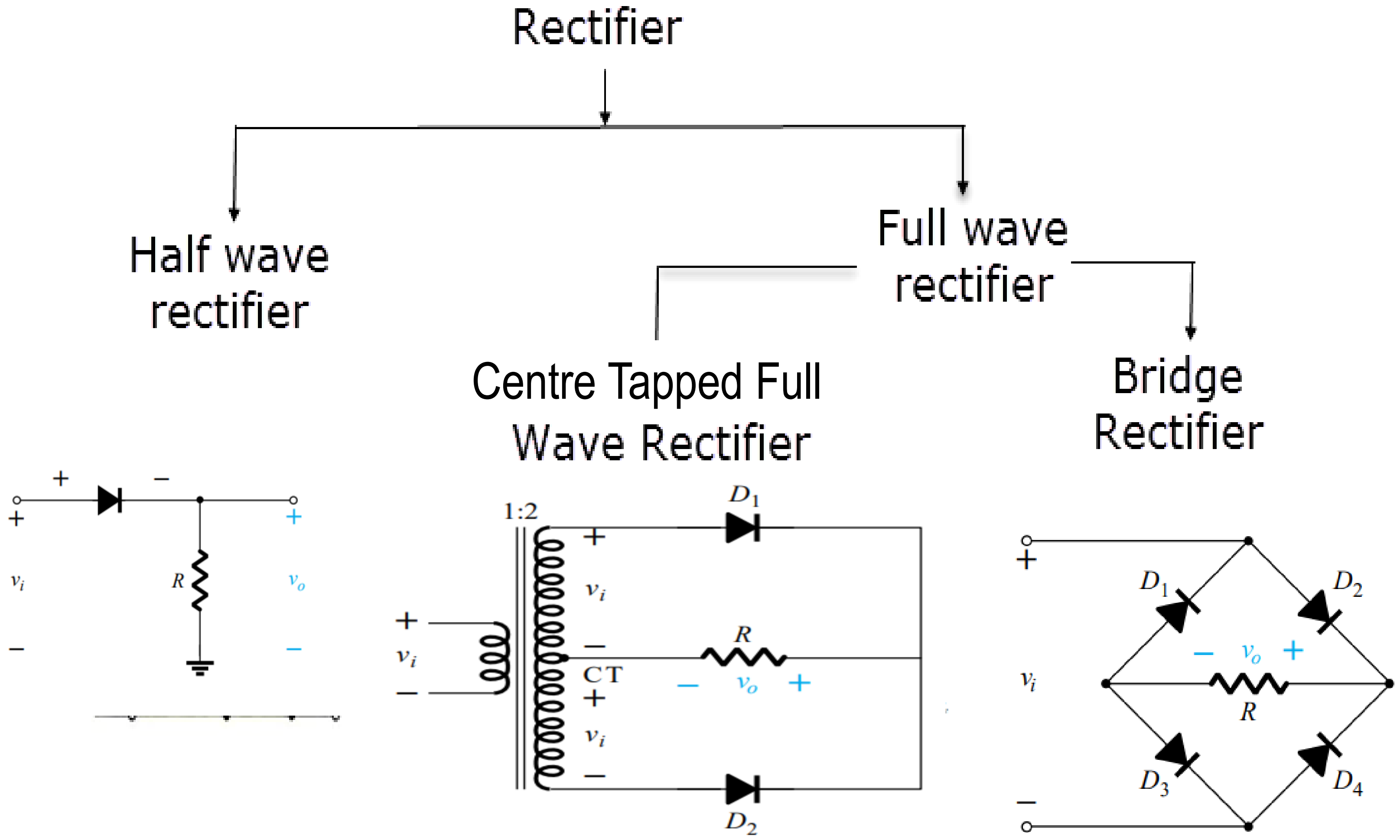
Regulated Power Supply

Regulated power supply converts an alternating current signal to a constant signal.

- **Transformer** : The output sinusoidal voltage is either step-up or step-down from the input sinusoidal voltage value
- **Rectifier** : Converts an alternating current into a direct one by allowing the current to flow through it in one direction only.
- **Filter** : Removes the AC ripples from the DC signal obtained from the rectifier.
- **Regulator** : Converts DC voltage into a lower constant voltage

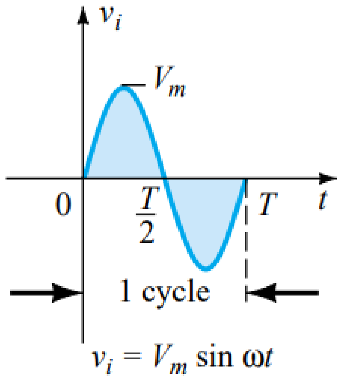
ELECTRONIC PRINCIPLES AND DEVICES

Rectifier

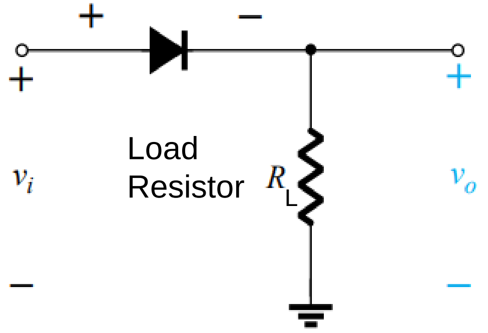


Half Wave Rectifier (HWR) - Ideal Diode

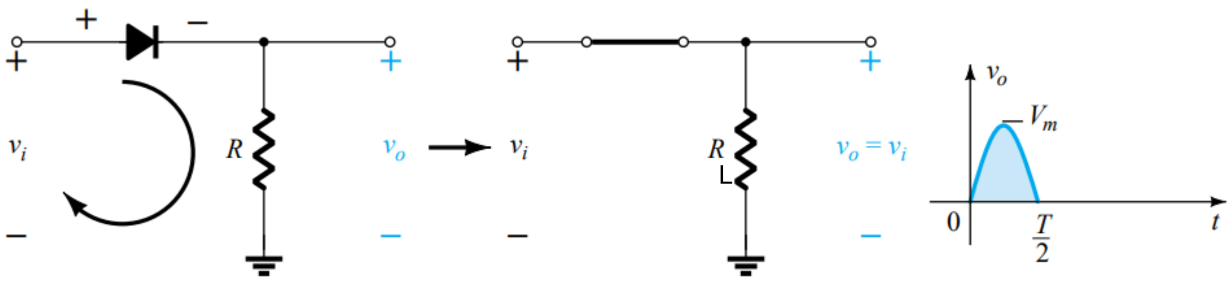
Input Waveform



HWR Circuit



Positive Half Cycle:

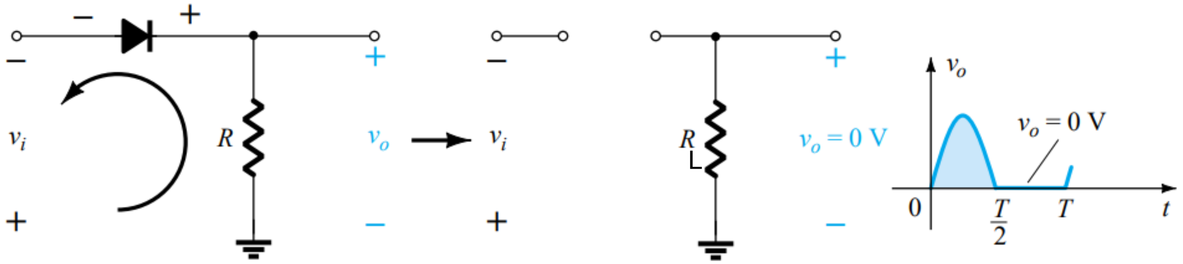


Conduction region ($0 \rightarrow T/2$).

$$I_m = \frac{V_m}{R_L}$$

$$V_o = V_m$$

Negative Half Cycle:



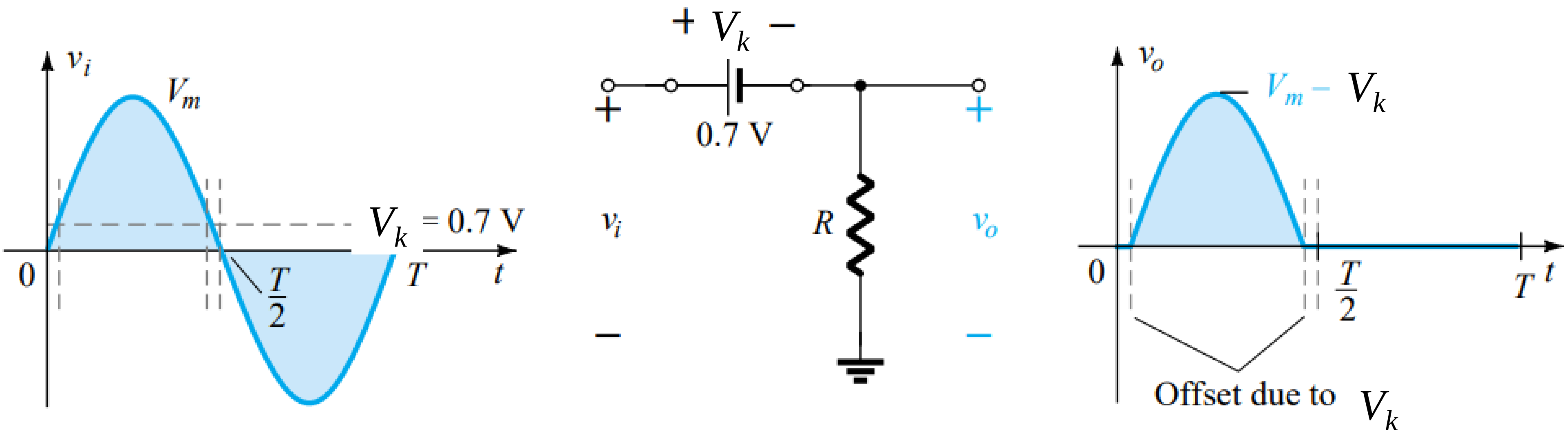
Nonconduction region ($T/2 \rightarrow T$).

I=0

$$V_o = 0$$

Half Wave Rectifier (HWR) - Non Ideal Diode

Positive Half Cycle:



Effect of V_k on half-wave rectified signal.

$$\mathbf{V_{omax} = V_m - V_k}$$

$$I_{omax} = \frac{V_m - V_k}{R_l}$$

Ripple factor of HWR

Ripple Factor is a measure of purity of the dc output of a rectifier and can be defined as

$$r = \frac{rms\ value\ of\ the\ ac\ \ component\ of\ the\ output}{average\ or\ dc\ value\ of\ the\ output}$$

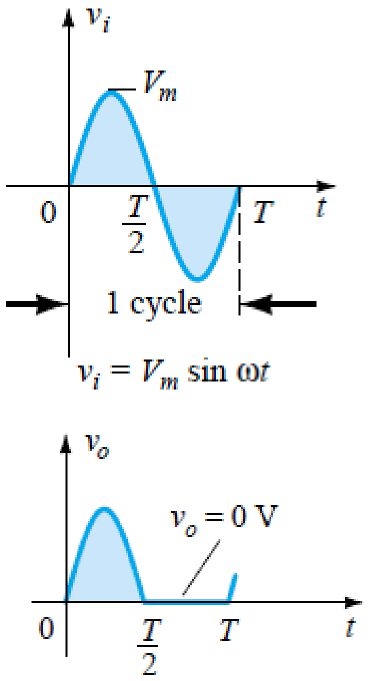
$$\text{Ripple Factor } (\Upsilon_{HWR}) = \frac{V'_{rms}}{V_{dc}} = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}}$$

Determining Average voltage/Current for HWR - Ideal Diode

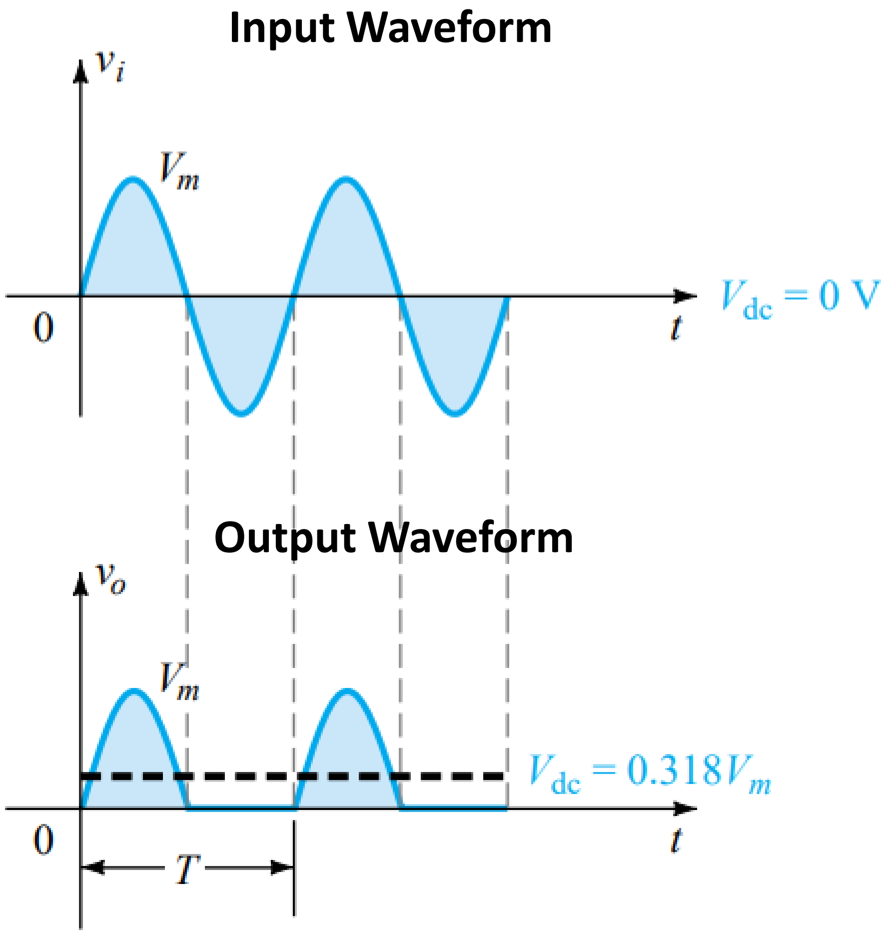
$$V_{dc} = \frac{1}{2\pi}\int_{0}^{2\pi} V_m \ sin\omega t \ d\omega t$$

$$= \frac{1}{2\pi}\int_{0}^{\pi} V_m \ sin\omega t \ d\omega t$$

$$= \frac{V_m}{2\pi}\ [-Cos\ \omega t]_0^{\pi} \ = \frac{V_m}{\pi}$$



Half Wave Rectifier (HWR) - Ideal Diode



$$V_{dc} = \frac{V_m}{\pi}$$

$$\boxed{V_{dc} = 0.318\,V_m} \quad \text{half-wave}$$

$$\boxed{I_{dc} = \frac{V_{dc}}{R_L} = \frac{V_m}{\pi R_L} = \frac{I_m}{\pi}}$$

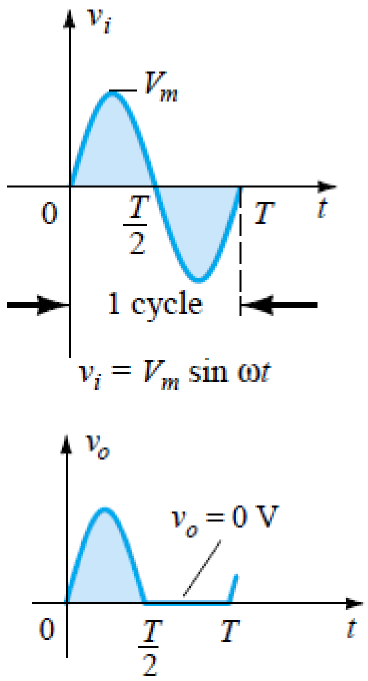
Determining RMS voltage/Current for HWR - Ideal Diode

$$V_{rms} = \left[\frac{1}{2\pi}\int_0^{2\pi}(V_m sin\omega t)^2\, d\omega t\right]^{1/2}$$

$$= \left[\frac{{V_m}^2}{2\pi}\int_0^{\pi}(sin^2\,\omega t)\ \ d\omega t\right]^{1/2}$$

$$= \left[\frac{{V_m}^2}{2\pi}\int_0^{\pi}\left(\frac{1 - Cos2\,\omega t}{2}\right)\ d\omega t\right]^{1/2}$$

$$V_{rms} = \left[\frac{{V_m}^2}{2\pi}\left(\frac{\omega t}{2} - \frac{sin2\omega t}{2}\right)_0^{\pi}\ \right]^{1/2} = \frac{V_m}{2}$$



$$\boxed{I_{rms} = \frac{V_{rms}}{R_L} = \frac{V_m}{2R_L} = \frac{I_m}{2}}$$

Determining Average & RMS voltage/Current for HWR – Non-Ideal Diode

$$V_{dc} = \frac{V_m - V_k}{\pi}$$

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{V_m - V_k}{\pi R_L} = \frac{I_m}{\pi} \qquad \left(I_m = \frac{V_m - V_k}{R_L} \right)$$

$$V_{rms} = \frac{V_m - V_k}{2}$$

$$I_{rms} = \frac{V_{rms}}{R_L} = \frac{V_m - V_k}{2R_L} = \frac{I_m}{2} \qquad \left(I_m = \frac{V_m - V_k}{R_L} \right)$$

Ripple factor of HWR

Ripple Factor is a measure of purity of the dc output of a rectifier and can be defined as

$$r = \frac{rms\ value\ of\ the\ ac\ component\ of\ the\ output}{average\ or\ dc\ value\ of\ the\ output}$$

$$V'_{rms} = \left[V_{rms}^2 - V_{dc}^2\right]^{1/2}$$

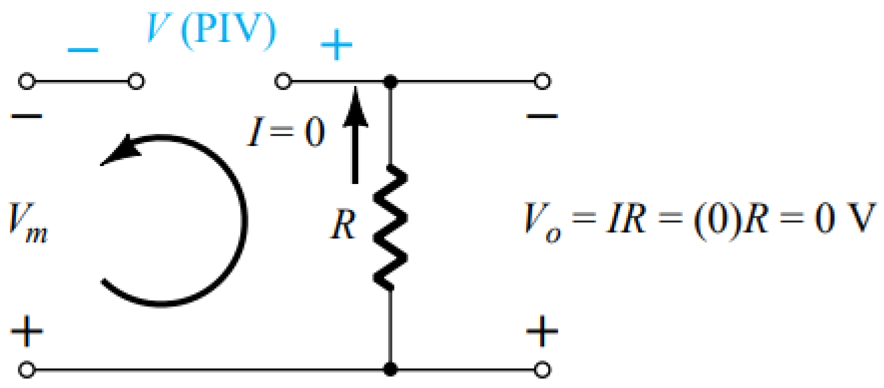
$$= \left[\left(\frac{V_m}{2}\right)^2 - \left(\frac{V_m}{\pi}\right)^2\right]^{1/2} = 0.385V_m$$

$$\text{Ripple Factor } (\Upsilon_{HWR}) = \frac{V'_{rms}}{V_{dc}} = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}}$$

$$= \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1} = \sqrt{\left(\frac{V_m/2}{V_m/\pi}\right)^2 - 1}$$

$\therefore$ Ripple factor =1.21

Half Wave Rectifier (HWR) PIV - Ideal Diode & Non Ideal Diode

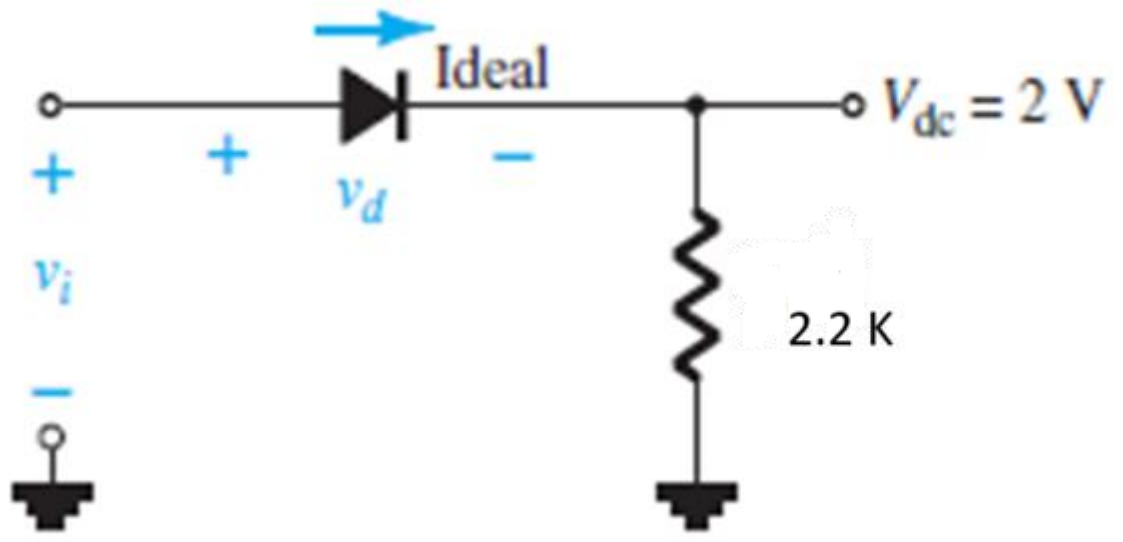


$$\boxed{\text{PIV rating} \geqq V_m}$$ half-wave rectifier

Peak Inverse Voltage (PIV) or Peak Reverse voltage (PRV)- (For both Ideal & Non-Ideal) is the maximum reverse biased voltage (Vm) the diode can withstand without entering the breakdown region.

Numerical on HWR

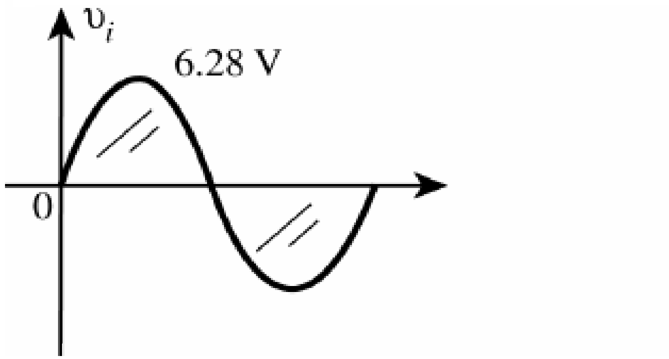
1. a) Assuming an ideal diode, sketch Vi, Vd, and id for the half-wave rectifier. The input is a sinusoidal waveform with a frequency of 60 Hz

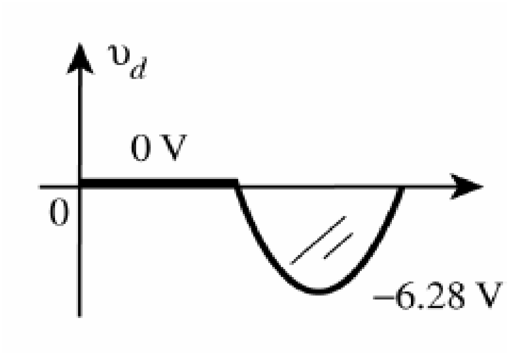


Numerical on HWR

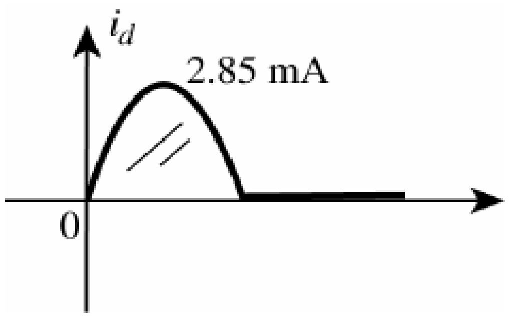
Solution:

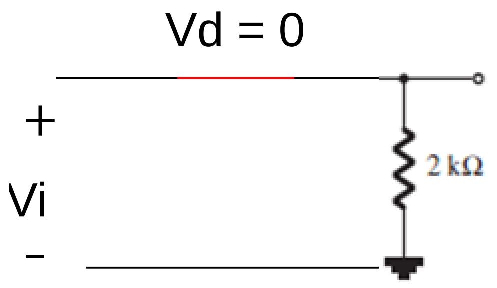
$$V_{dc} = 0.318\,V_m \Rightarrow V_m = \frac{V_{dc}}{0.318} = \frac{2\text{ V}}{0.318} = \mathbf{6.28\ V}$$

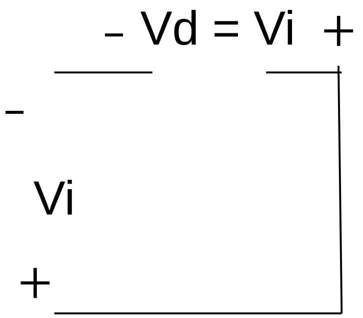




$$I_m = \frac{V_m}{R} = \frac{6.28\text{ V}}{2.2\text{ k}\Omega} = \mathbf{2.85\ mA}$$

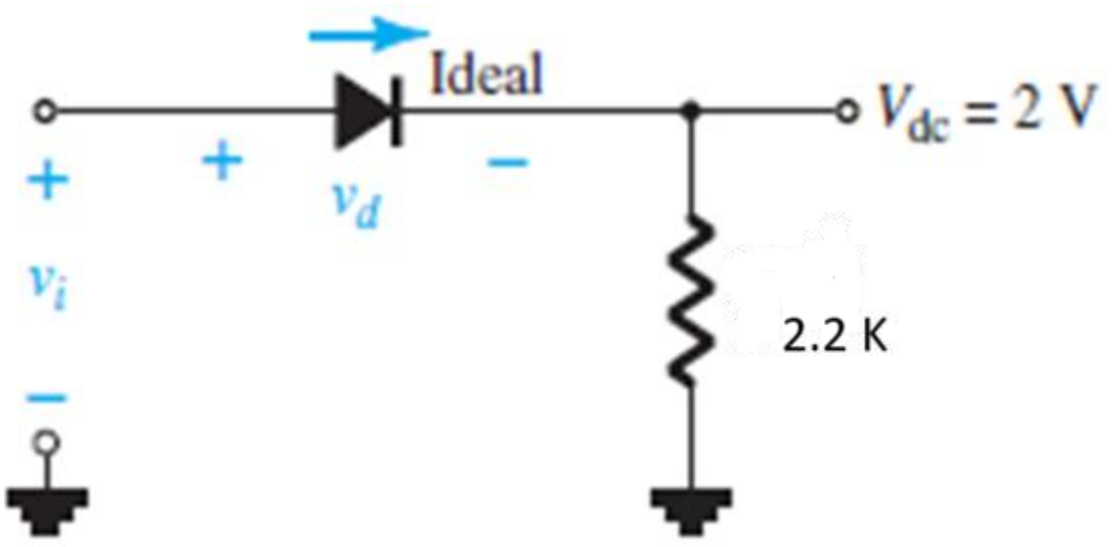






Numerical on HWR

1. b) Assuming a silicon diode (V_k=0.7 V), sketch *vi*, *vd*, and *id* for the half-wave rectifier . The input is a sinusoidal waveform with a frequency of 60 Hz



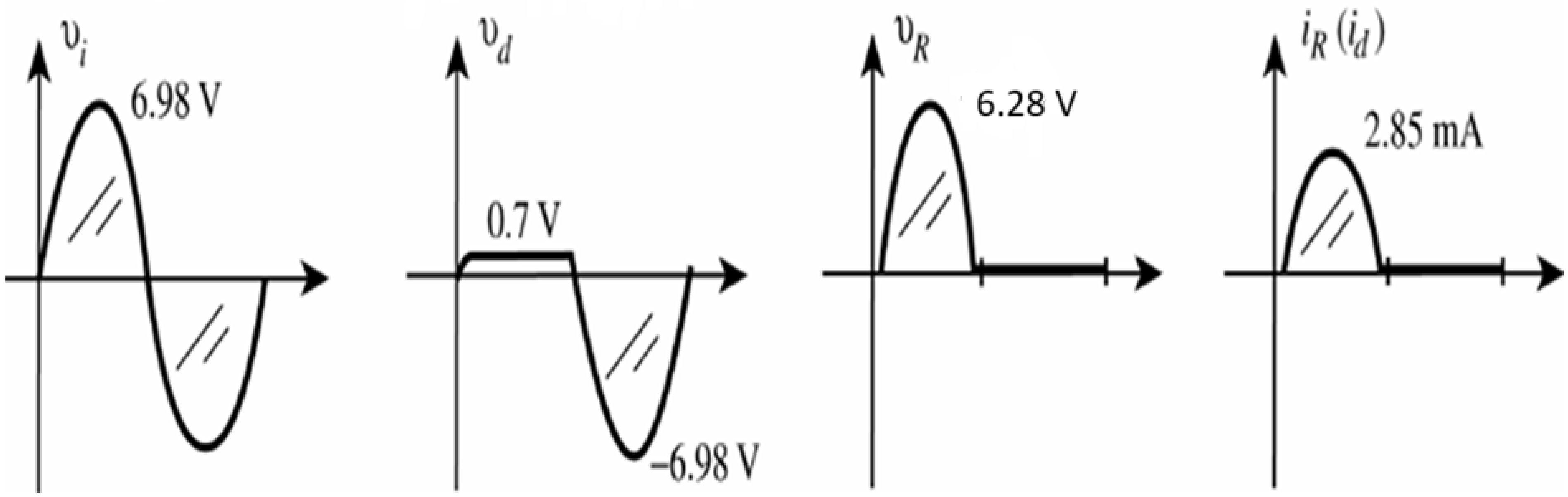
Numerical on HWR

Solution:

Using $V_{dc} \cong 0.318(V_m - V_K)$

$$2\text{ V} = 0.318(V_m - 0.7\text{ V})$$

Solving: $V_m = \mathbf{6.98\ V}$



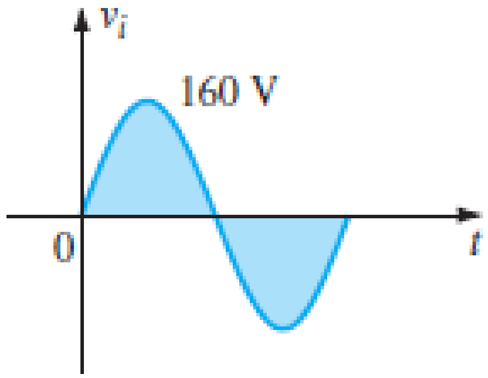
Numerical on HWR

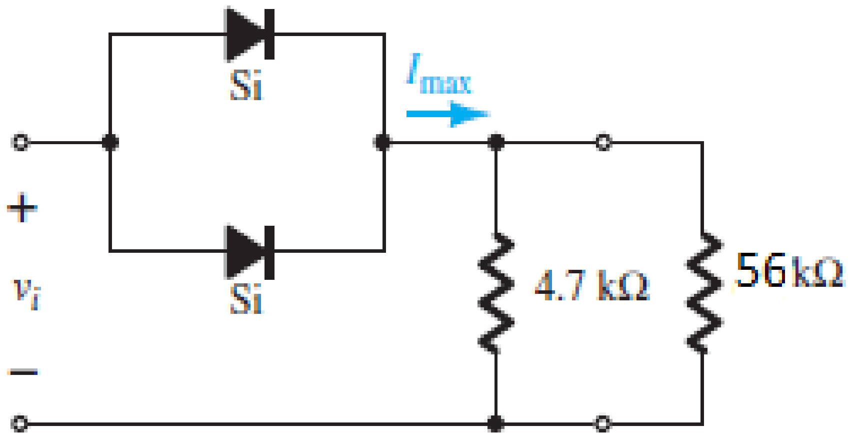
2. (a) Given Pmax= 14 mW for each diode shown, determine the maximum current rating of each diode (using the approximate equivalent model).

(b) Determine Imax for Vimax =160 V.

(c) Determine the current through each diode at Vimax using the results of part (b).

(d) If only one diode were present, determine the diode current and compare it to the maximum rating.





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Solution:

(a) $P_{max} = 14\text{ mW} = (0.7\text{ V})I_D$

$$I_D = \frac{14\text{ mW}}{0.7\text{ V}} = \mathbf{20\text{ mA}}$$

(b) $4.7\text{ k}\Omega \parallel 56\text{ k}\Omega = 4.34\text{ k}\Omega$

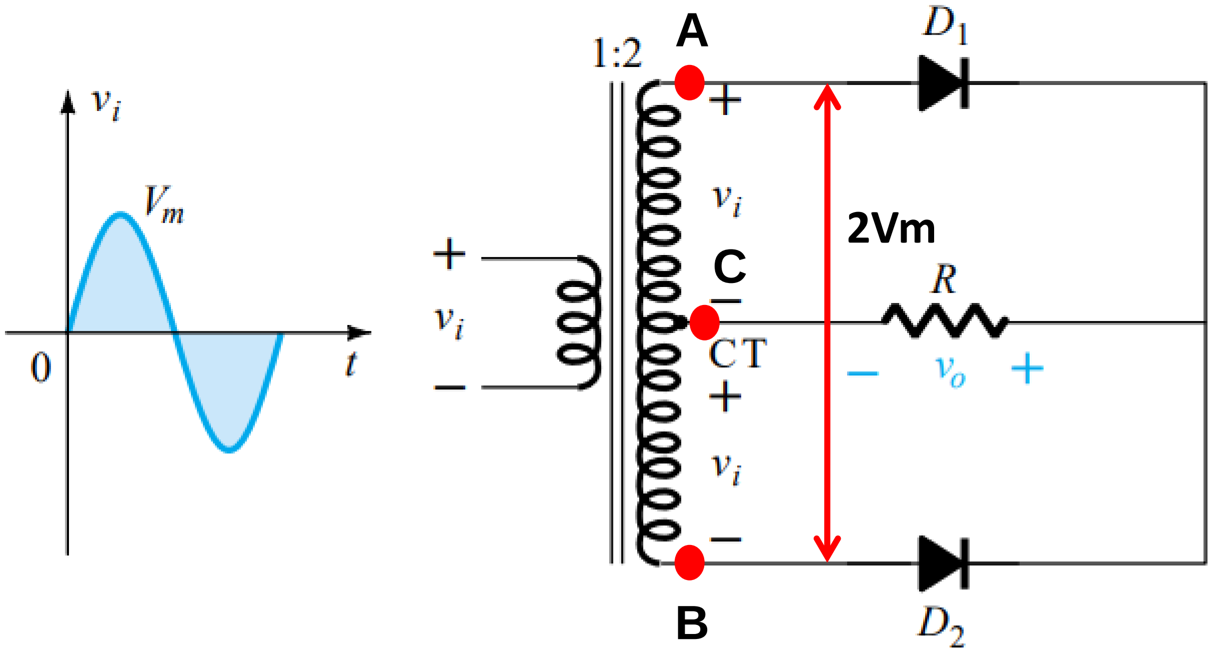
$V_R = 160\text{ V} - 0.7\text{ V} = 159.3\text{ V}$

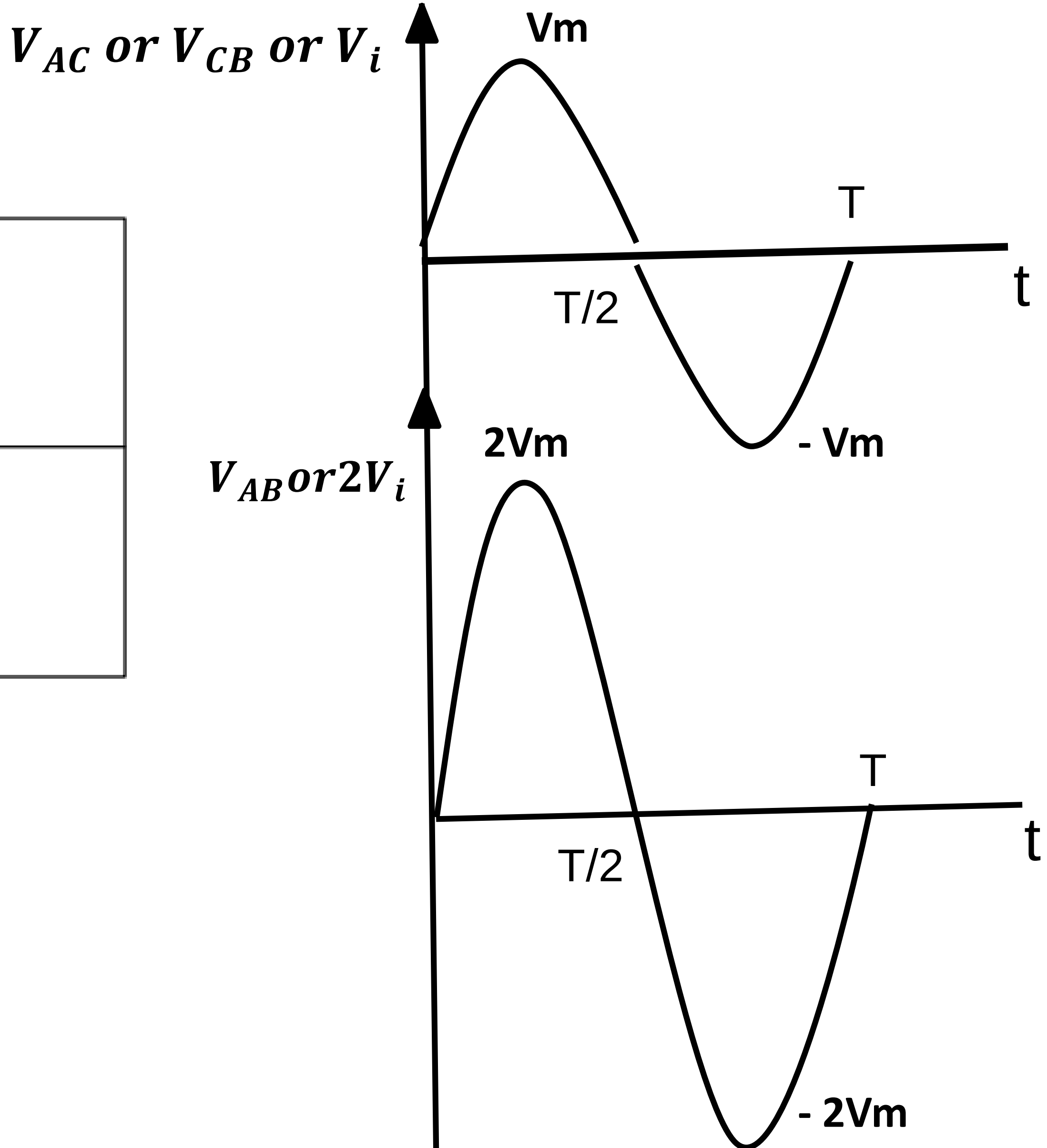
$$I_{max} = \frac{159.3\text{ V}}{4.34\text{ k}\Omega} = \mathbf{36.71\text{ mA}}$$

(c) $$I_{diode} = \frac{I_{max}}{2} = \frac{36.71\text{ mA}}{2} = \mathbf{18.36\text{ mA}}$$ $I_D = 20\text{ mA} > 18.36\text{ mA}$

(d) $I_{diode} = 36.71\text{ mA} \gg I_{max} = 20\text{ mA}$ Total damage

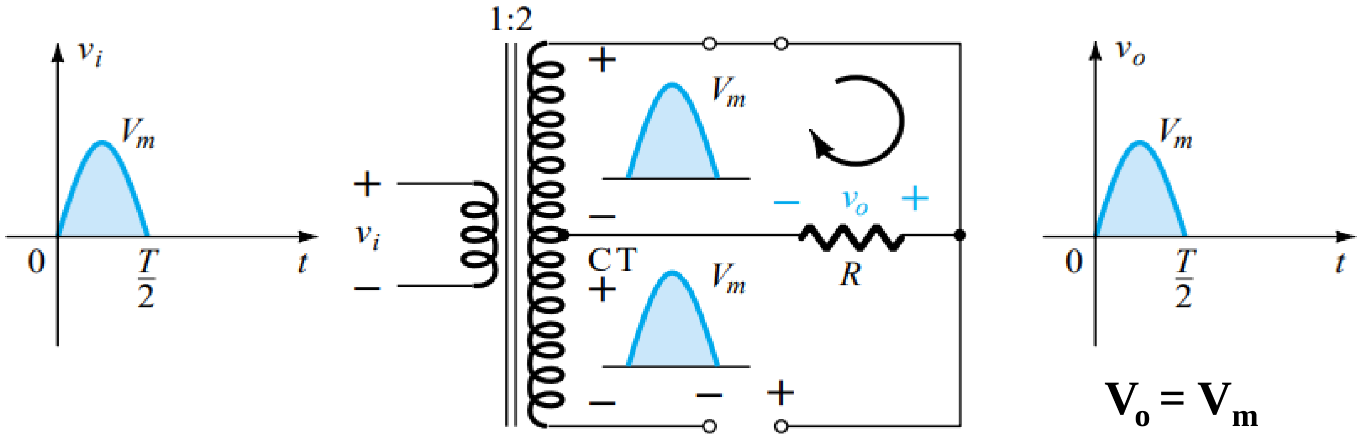
Full Wave Rectifier : Centre Tap (Ideal Diode)





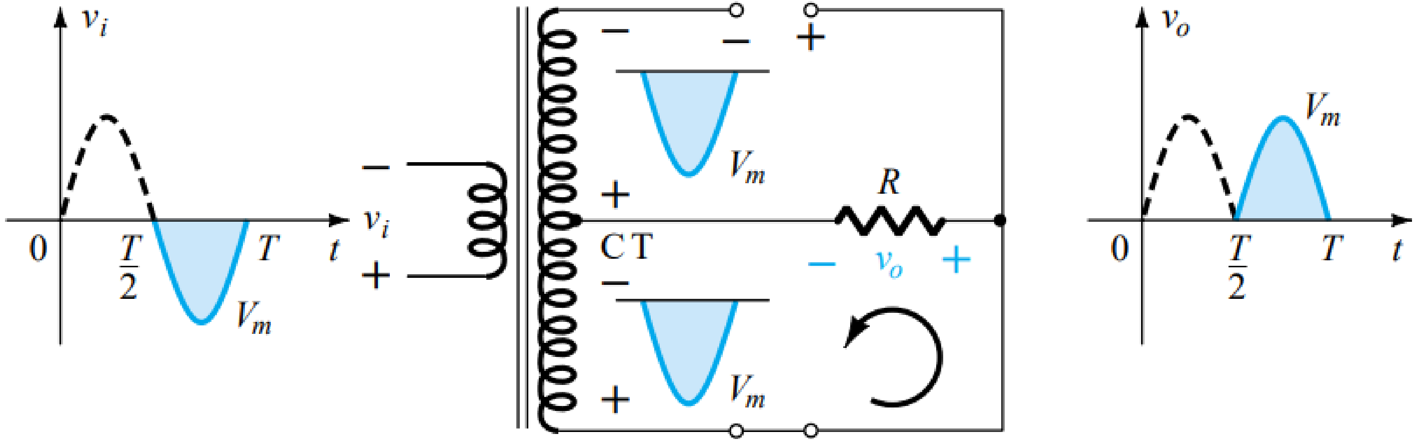
Full Wave Rectifier : Centre Tap (Ideal Diode)

Positive Half Cycle:



$\mathbf{V_o = V_m}$ $\qquad$ $\mathbf{I_o} = \frac{\mathbf{V_m}}{R_L}$

Negative Half Cycle:

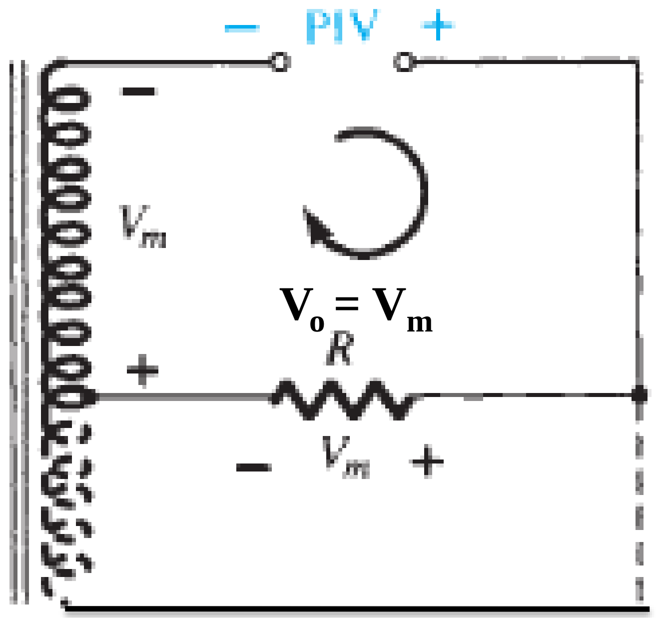


$\mathbf{V_o = V_m}$

$\mathbf{I_m} = \frac{\mathbf{V_m}}{R_L}$

Full Wave Rectifier PIV - Centre Tap (Ideal Diode)

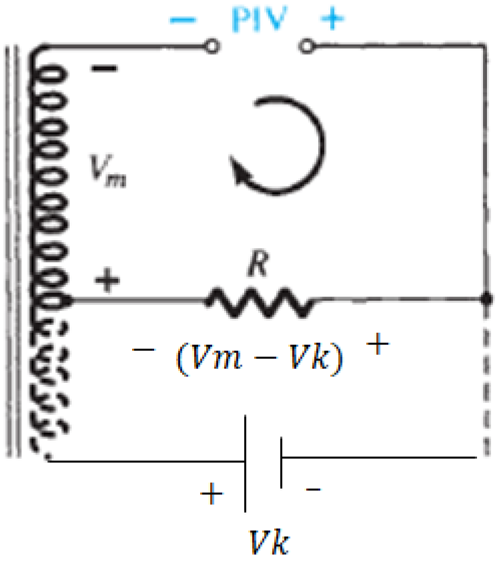
$$\begin{aligned} \text{PIV} &= V_{\text{secondary}} + V_R \\ &= V_m + V_m \end{aligned}$$



$\boxed{\text{PIV} \geqq 2V_m}$ CT transformer, full-wave rectifier

Full Wave Rectifier : Centre Tap (Non Ideal Diode)

Negative Half Cycle:



$$V_{o\,max} = V_m - V_k$$

$$I_{o\,max} = \frac{V_m - V_k}{R_L}$$

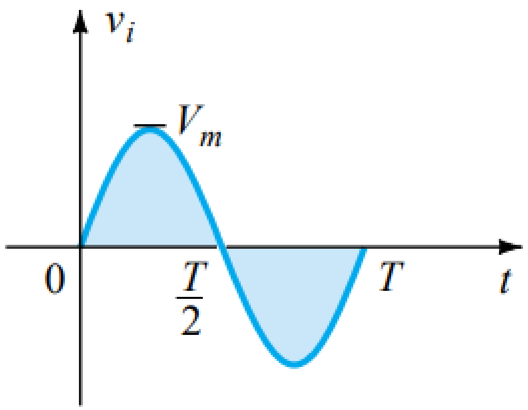
$$\text{PIV} - Vm + Vk - Vm = 0$$

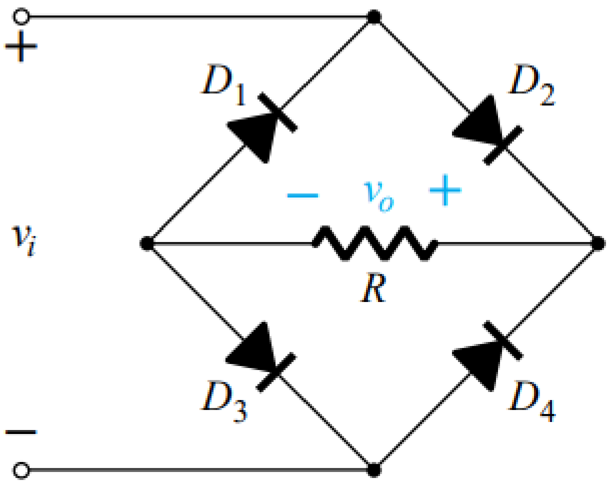
$$\text{PIV} - 2Vm + Vk = 0$$

$$\text{PIV} = 2Vm - Vk$$

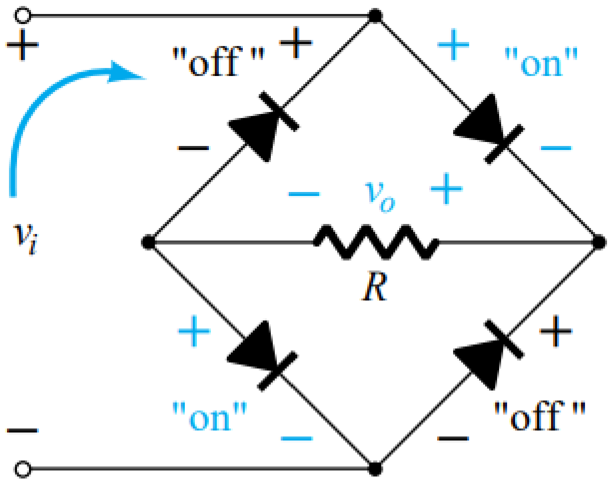
$$Non - Ideal\ diode\text{: PIV} \geq 2Vm - Vk$$

Full Wave Rectifier: Bridge Rectifier (Ideal Diode)



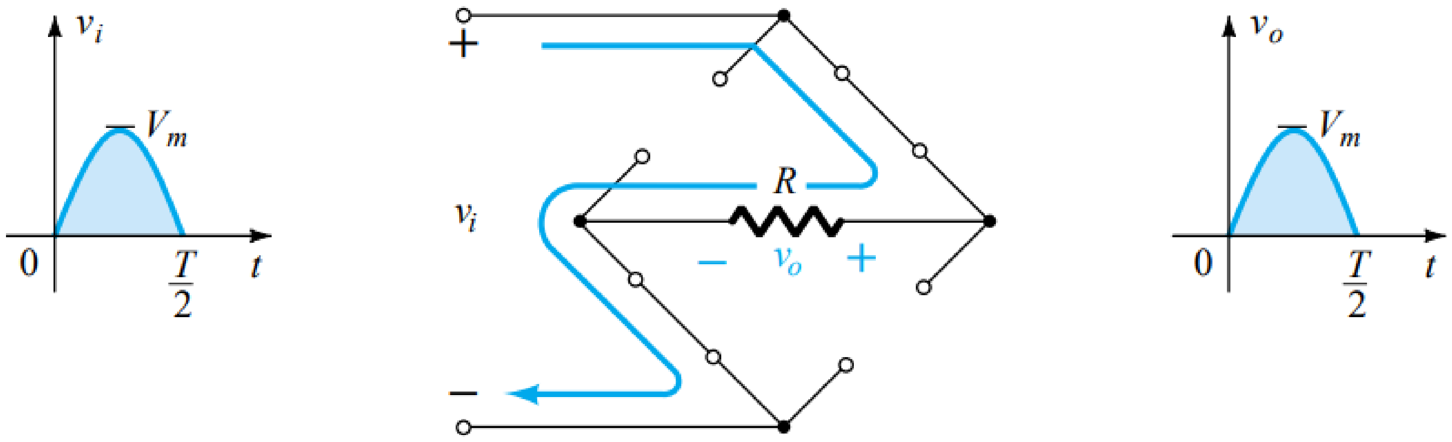


Positive Half Cycle:

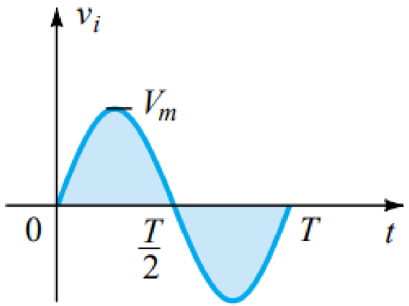


Full Wave Rectifier: Bridge Rectifier (Ideal Diode)

Positive Half Cycle:



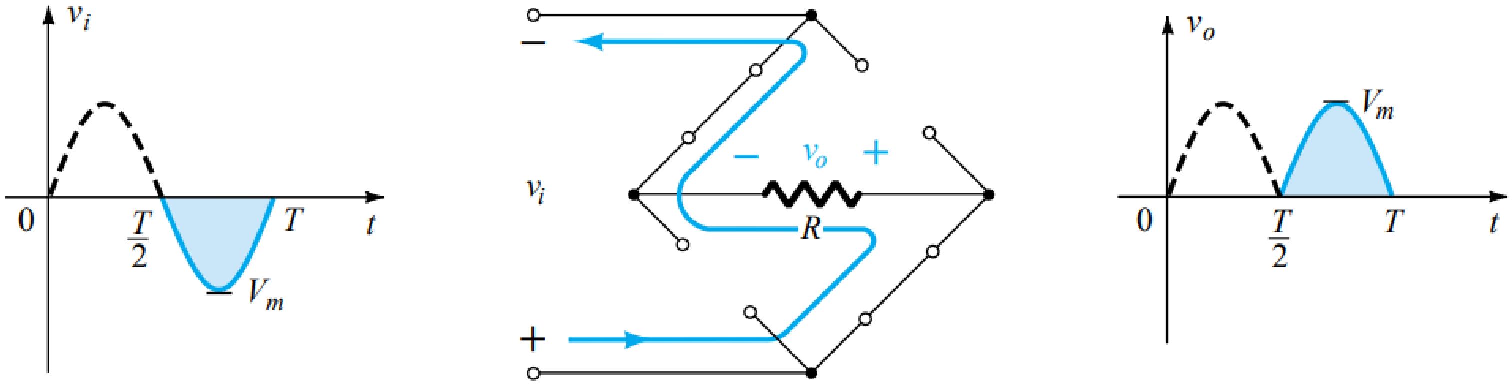
Input Waveform



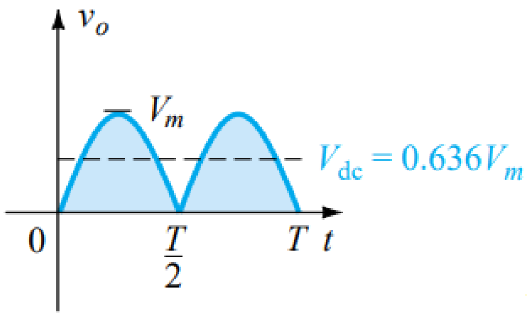
$$V_o = V_m$$

$$I_o = \frac{V_m}{R_L}$$

Negative Half Cycle:

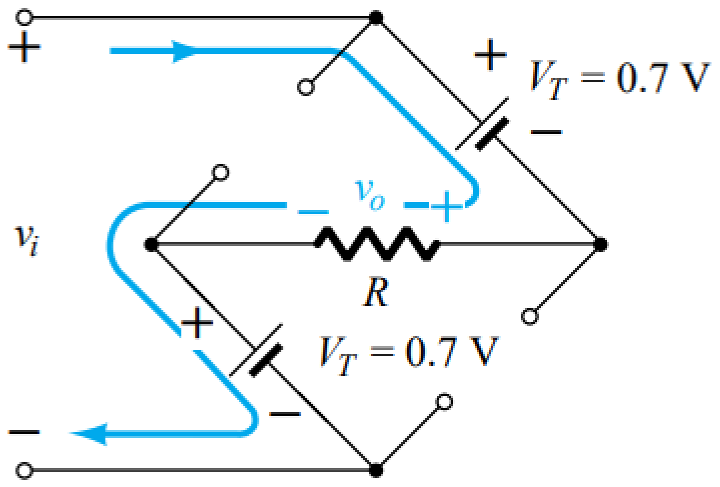


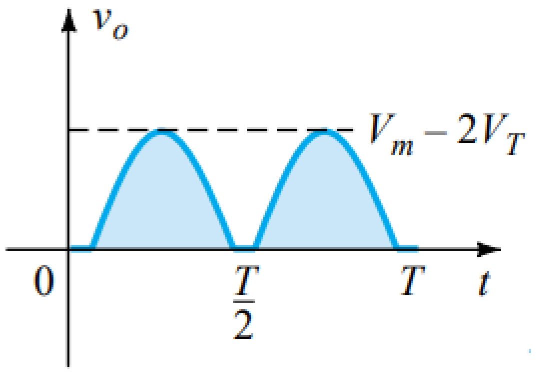
Output Waveform



Full Wave Rectifier: Bridge Rectifier (Non Ideal Diode)

$$V_{dc} \cong 0.636(V_m - 2V_T)$$





$$v_i - V_T - v_o - V_T = 0$$

$$v_o = v_i - 2V_T$$

$$V_{o_{max}} = V_m - 2V_T$$

Full Wave Rectifier PIV : Bridge Rectifier (Ideal & Non-Ideal Diode)

Ideal diode: $\boxed{\text{PIV} \geqq V_m}$ full-wave bridge rectifier

$$\text{PIV} - Vm = 0$$

$$\text{PIV} = Vm$$

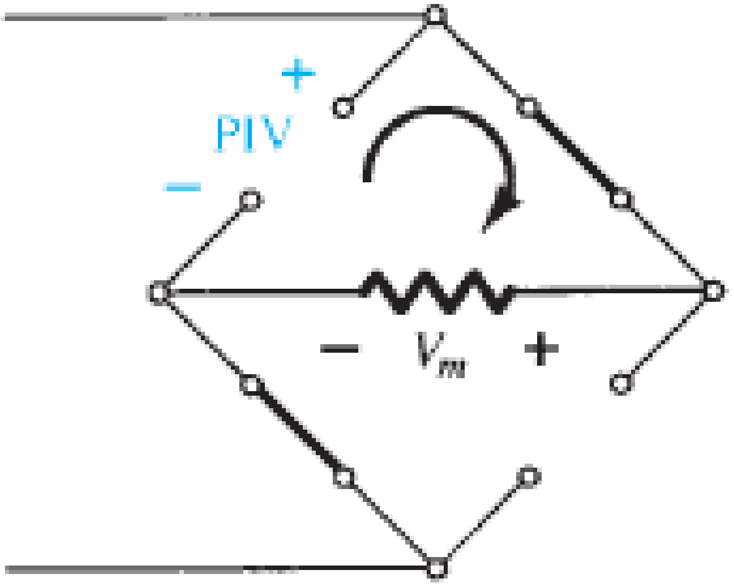
Non − Ideal diode: $\text{PIV} \geq Vm - Vk$

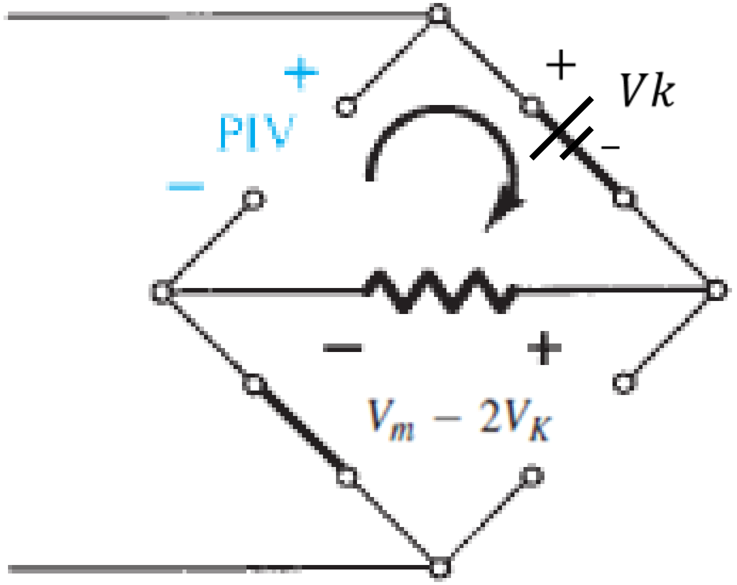
$$\text{PIV} - Vk - Vo = 0$$

$$\text{PIV} - Vk - Vm + 2Vk = 0$$

$$\text{PIV} + Vk - Vm = 0$$

$$\text{PIV} = Vm - Vk$$





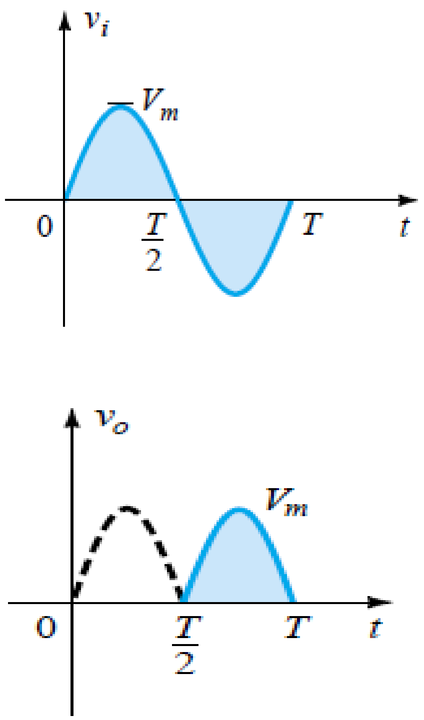
Determining Average voltage/ current for FWR (Ideal Diode)

$$V_{dc} = \frac{2}{2\pi} \int_{0}^{\pi} V_m \; sin\omega t \; d\omega t$$

$$= \frac{V_m}{\pi} \left[-Cos\ \omega t \right]_0^{\pi}$$

$$= \frac{2V_m}{\pi}$$

$$\boxed{I_{dc} = \frac{V_{dc}}{R} = \frac{2V_m}{\pi R} = \frac{2I_m}{\pi}}$$

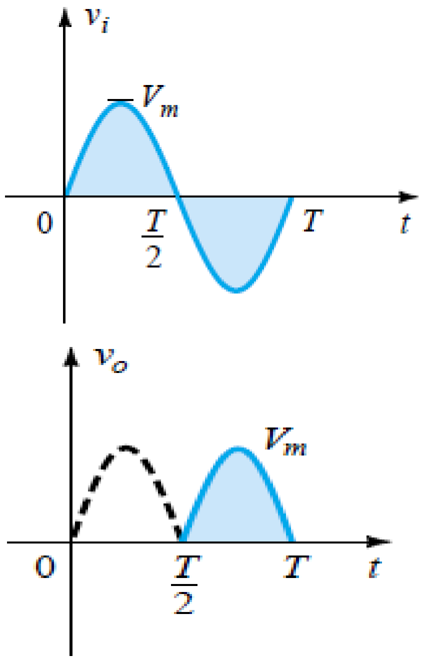


Determining RMS voltage/ current for FWR (Ideal Diode)

$$V_{rms} = \left[\frac{1}{\pi}\int_0^{\pi}(V_m sin\omega t)^2\ d\omega t\right]^{1/2}$$

$$= \left[\frac{2V_m^{\ 2}}{2\pi}\int_0^{\pi}\left(\frac{1 - Cos2\,\omega t}{2}\right)\ d\omega t\right]^{1/2}$$

$$= \left[\frac{V_m^{\ 2}}{2\pi}\int_0^{\pi}(1 - Cos2\,\omega t)\ \ d\omega t\right]^{1/2}$$



$$= \left[\frac{V_m^{\ 2}}{2\pi}\left(\omega t_0^{\pi} - \frac{Sin2\,\omega t^{\pi}}{2}\bigg|_0\right)\right]^{1/2} = \left[\frac{V_m^{\ 2}}{2\pi}\ (\pi - 0)\ \right]^{1/2} = \frac{V_m}{\sqrt{2}}$$

$$I_{rms} = \frac{V_{rms}}{R} = \frac{V_m}{\sqrt{2}R} = \frac{I_m}{\sqrt{2}}$$

Average & RMS voltage/Current for Centre Tap Rectifier - Non Ideal Diode

$$V_{dc} = \frac{2(V_m - V_k)}{\pi}$$

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{2(V_m - V_k)}{\pi R_L} = 2\frac{I_m}{\pi} \qquad \left(I_m = \frac{V_m - V_k}{R_L}\right)$$

$$V_{rms} = \frac{V_m - V_k}{\sqrt{2}}$$

$$I_{rms} = \frac{V_{rms}}{R_L} = \frac{V_m - V_k}{\sqrt{2} R_L} = \frac{I_m}{\sqrt{2}} \qquad \left(I_m = \frac{V_m - V_k}{R_L}\right)$$

Average & RMS voltage/Current for Bridge Rectifier- Non ideal Diode

$$V_{dc} = \frac{2(V_m - 2V_k)}{\pi}$$

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{2(V_m - 2V_k)}{\pi R_L} = 2\frac{I_m}{\pi} \qquad (I_m = \frac{V_m - 2V_k}{R_L})$$

$$V_{rms} = \frac{V_m - 2V_k}{\sqrt{2}}$$

$$I_{rms} = \frac{V_{rms}}{R_L} = \frac{V_m - 2V_k}{\sqrt{2}R_L} = \frac{I_m}{\sqrt{2}} \qquad (I_m = \frac{V_m - 2V_k}{R_L})$$

Ripple factor of FWR

Ripple Factor is a measure of purity of the dc output of a rectifier and can be defined as

$$r = \frac{rms\ value\ of\ the\ ac\ component\ of\ the\ output}{average\ or\ dc\ value\ of\ the\ output}$$

$$V'_{rms} = \sqrt{V_{rms}^2 - V_{dc}^2}$$

$$= \sqrt{\left(\frac{V_m}{\sqrt{2}}\right)^2 - \left(\frac{2V_m}{\pi}\right)^2} = 0.307\ V_m$$

Ripple Factor $(\Upsilon_{FWR}) = \frac{V'_{rms}}{V_{dc}} =$

$$= \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1} = \sqrt{\left(\frac{V_m/\sqrt{2}}{2V_m/\pi}\right)^2 - 1}$$

∴ Ripple factor =0.48

Comparison Table for HWR & FWR

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Measure	HWR Ideal	HWR Practical	CT-Ideal	CT-Practical	Bridge- Ideal	Bridge-Practical
I_{dc}	$\frac{I_m}{\pi}$	$\frac{I_m}{\pi}$	$\frac{2I_m}{\pi}$	$\frac{2I_m}{\pi}$	$\frac{2I_m}{\pi}$	$\frac{2I_m}{\pi}$
V_{dc}	$\frac{V_m}{\pi}$	$\frac{V_m - V_k}{\pi}$	$\frac{2V_m}{\pi}$	$\frac{2(V_m - V_k)}{\pi}$	$\frac{2V_m}{\pi}$	$\frac{2(V_m - 2V_k)}{\pi}$
I_{rms}	$\frac{I_m}{2}$	$\frac{I_m}{2}$	$\frac{I_m}{\sqrt{2}}$	$\frac{I_m}{\sqrt{2}}$	$\frac{I_m}{\sqrt{2}}$	$\frac{I_m}{\sqrt{2}}$
V_{rms}	$\frac{V_m}{2}$	$\frac{V_m - V_k}{2}$	$\frac{V_m}{\sqrt{2}}$	$\frac{V_m - V_k}{\sqrt{2}}$	$\frac{V_m}{\sqrt{2}}$	$\frac{V_m - 2V_k}{\sqrt{2}}$
PIV	V_m	V_m	$2V_m$	$2V_m - V_k$	V_m	$V_m - V_k$

Differences between Centre Tap & Bridge FWR

Sl No.`	Bridge-FWR	CT- FWR
1	Lesser PIV	Comparatively higher PIV
2	Centre tap transformer not required	Centre tap transformer required
3	Uniform input for both half cycles	Difficult to balance both the half cycles due to CT
4	4 diodes are required	2 diodes are required
5	More voltage drop due to two diodes in the path	Comparatively less voltage drop due to only one diode in the path

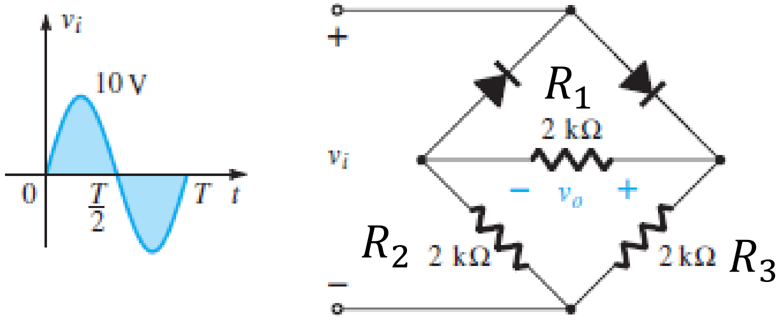
Differences between Ideal V_{DC} Non-Ideal V_{DC}

Rectifier	Ideal V_{DC}	Non-Ideal V_{DC}
Half Wave Rectifier	$V_{DC} = 0.318\ V_m$	$V_{DC} = 0.318\ V_m - 0.7$
Bridge Rectifier	$V_{DC} = 0.636\ V_m$	$V_{DC} = 0.636\ V_m - 2(0.7\ V)$
Center-Tapped Transformer Rectifier	$V_{DC} = 0.636\ V_m$	$V_{DC} = 0.636\ V_m - 0.7\ V$

ELECTRONIC PRINCIPLES AND DEVICES

Numerical on Full Wave Rectifier: Bridge Rectifier

1.Determine the output waveform for the network and calculate the output dc level.

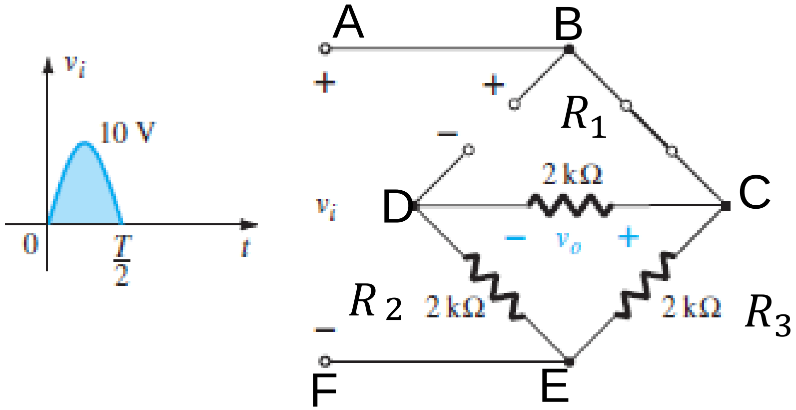


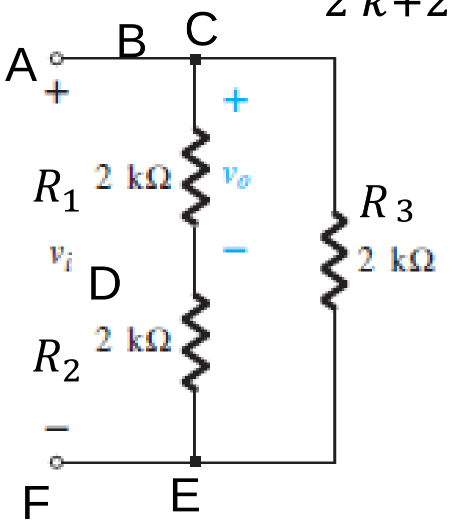
Solution:

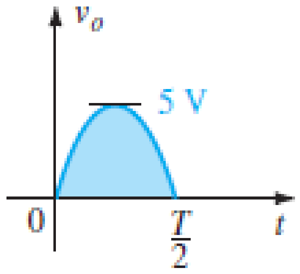
$$Voltage\ Divider\ Rule: \frac{V_i R_1}{R_1 + R_2} = V_0$$

$$V_0 = \frac{10(2\,k)}{2\,k + 2\,k} = 5\text{ V}$$

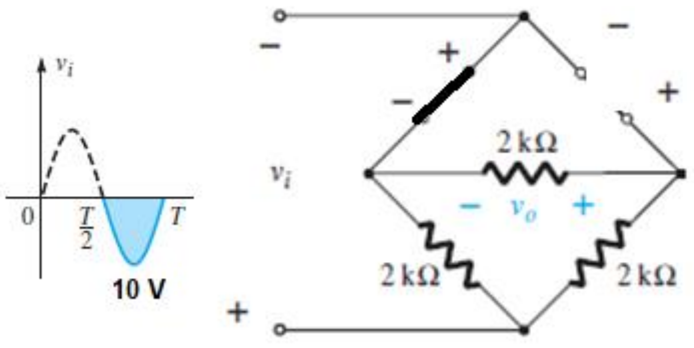
Vomax = (2/4) Vimax = (2/4) (10 V) = 5 V

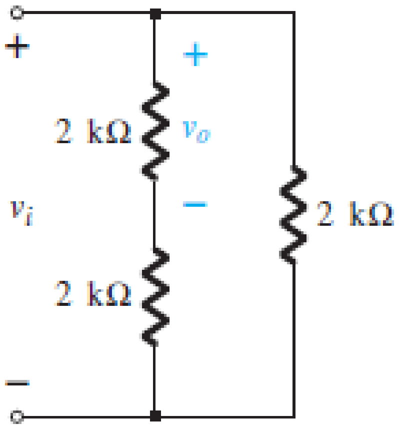


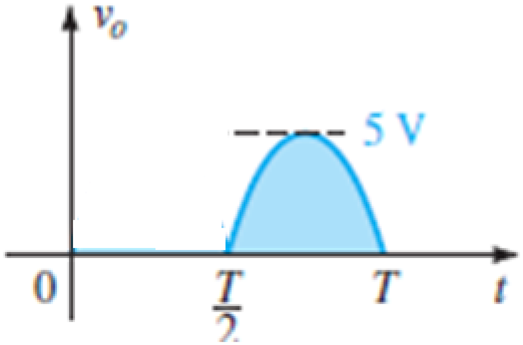


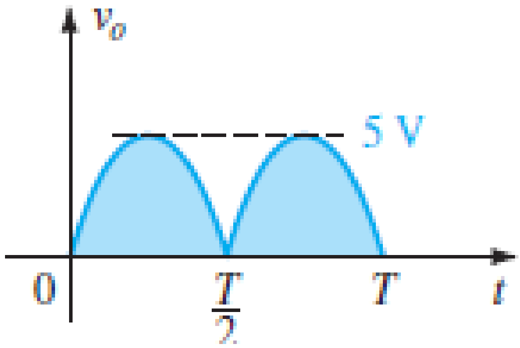


Numerical on Full Wave Rectifier: Bridge Rectifier





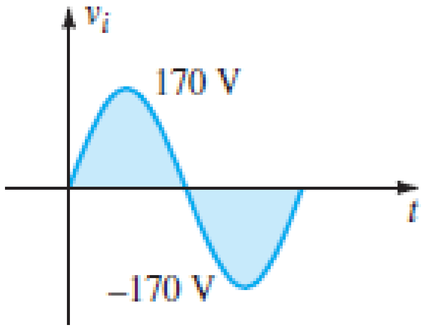


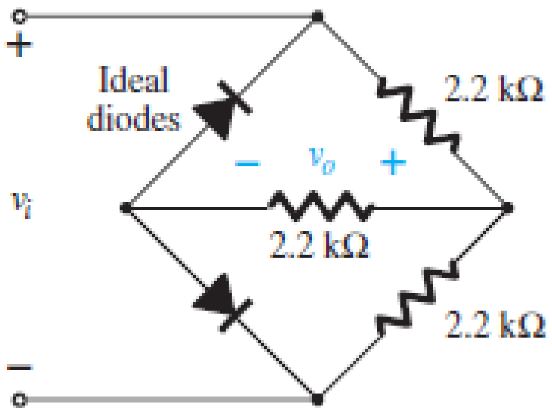


$$V_{dc} = 0.636(5\ \text{V}) = 3.18\ \text{V}$$

Numerical on Full Wave Rectifier: Bridge Rectifier

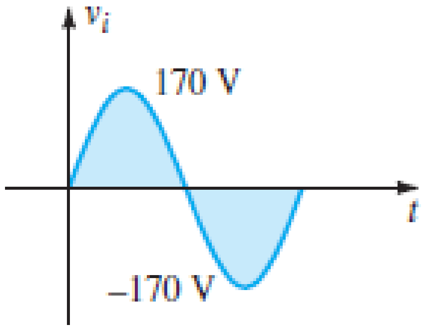
Sketch v_o for the network

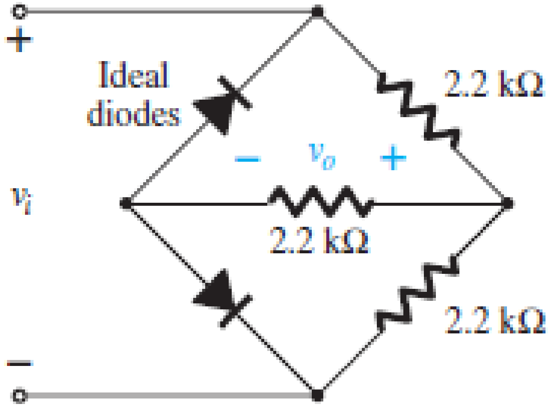


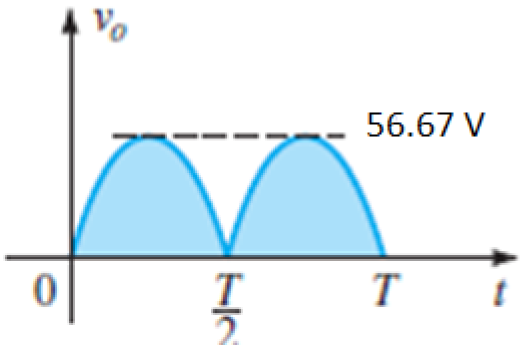


Numerical on Full Wave Rectifier: Bridge Rectifier

Sketch v_o for the network







Positive pulse of v_i:

Top left diode "off", bottom left diode "on"

$2.2\ \text{k}\Omega \parallel 2.2\ \text{k}\Omega = 1.1\ \text{k}\Omega$

$$V_{o_{\text{peak}}} = \frac{1.1\ \text{k}\Omega(170\ \text{V})}{1.1\ \text{k}\Omega + 2.2\ \text{k}\Omega} = 56.67\ \text{V}$$

Negative pulse of v_i:

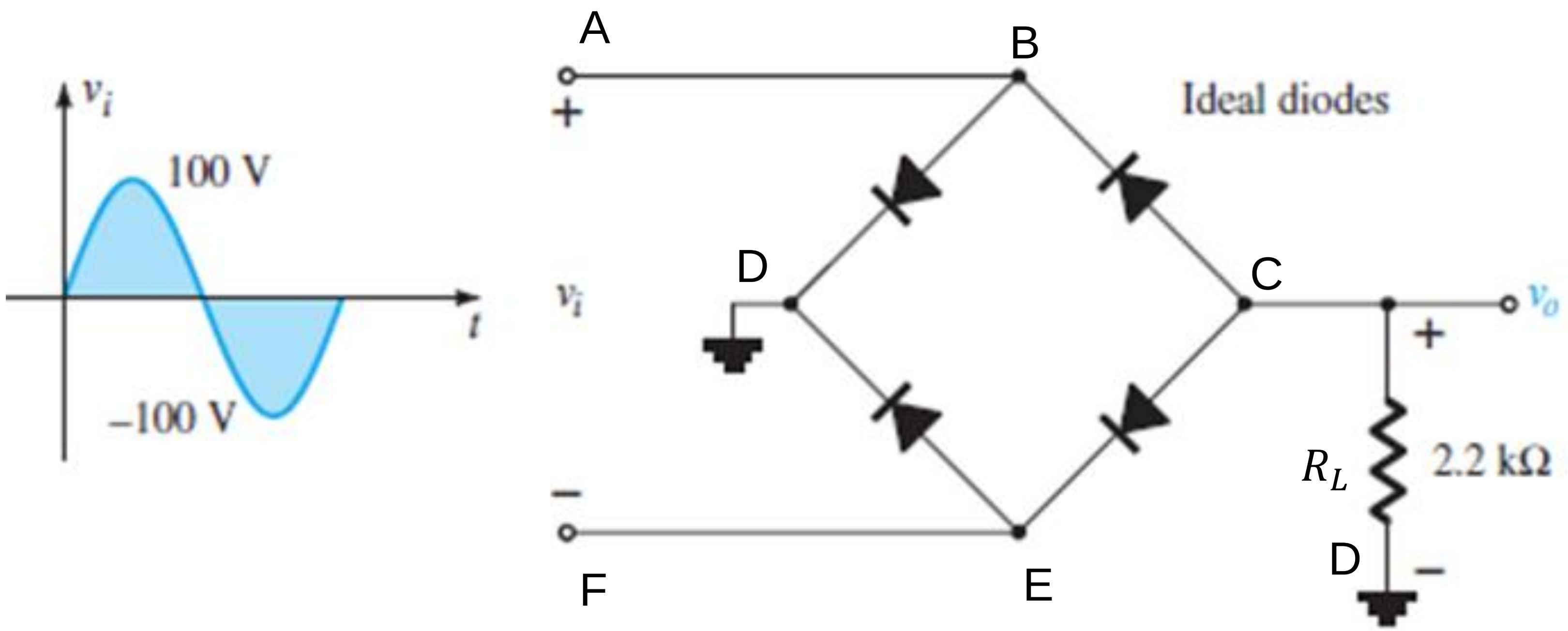
Top left diode "on", bottom left diode "off"

$$V_{o_{\text{peak}}} = \frac{1.1\ \text{k}\Omega(170\ \text{V})}{1.1\ \text{k}\Omega + 2.2\ \text{k}\Omega} = 56.67\ \text{V}$$

$V_{dc} = 0.636(56.67\ \text{V}) = \mathbf{36.04\ V}$

Full Wave Rectifier

3.Determine Vo and the required PIV rating of each diode for the configuration of Fig. In addition, determine the maximum current through each diode.



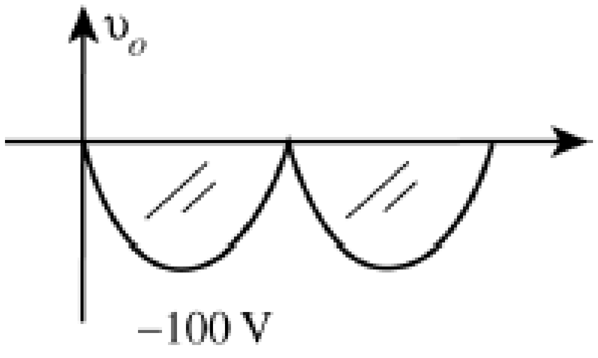
For positive cycle
Path : ABDCEF

Applying KVL

$$V_i + V_0 = 0\ ;\ V_0 = -V_i$$

For Negative cycle:
Path : FEDCBA

Numerical on Full Wave Rectifier: Bridge Rectifier

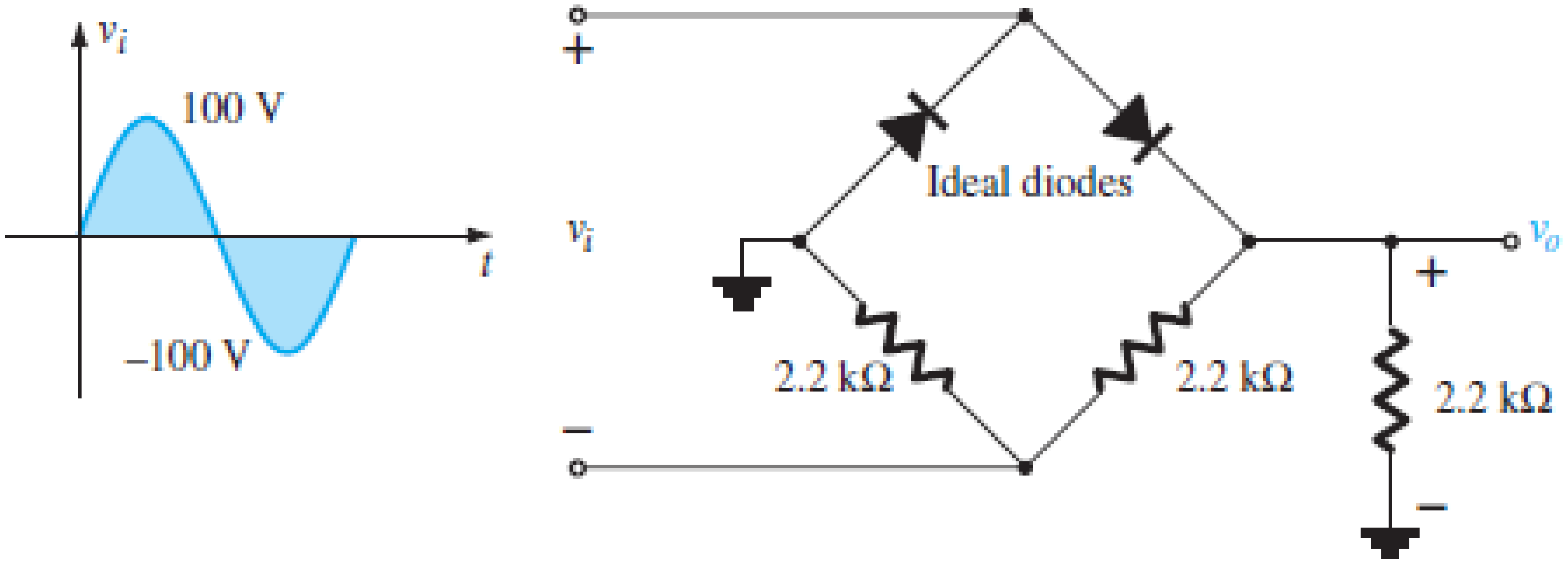


$$\text{PIV} = \mathbf{100\ V}$$

$$I_{\text{max}} = \frac{100\ \text{V}}{2.2\ \text{k}\Omega} = \mathbf{45.45\ mA}$$

Numerical on Full Wave Rectifier: Bridge Rectifier

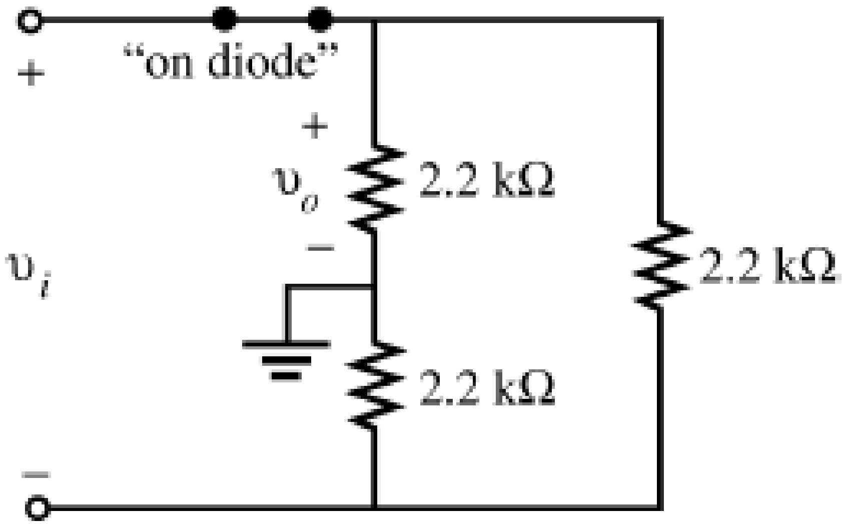
4.Sketch Vo for the network of Fig. and determine the dc voltage available.



Numerical on Full Wave Rectifier: Bridge Rectifier

Positive half-cycle of v_i:

Network redrawn:



Voltage-divider rule:

$$V_{o_{\max}} = \frac{2.2\ \text{k}\Omega (V_{i_{\max}})}{2.2\ \text{k}\Omega + 2.2\ \text{k}\Omega}$$

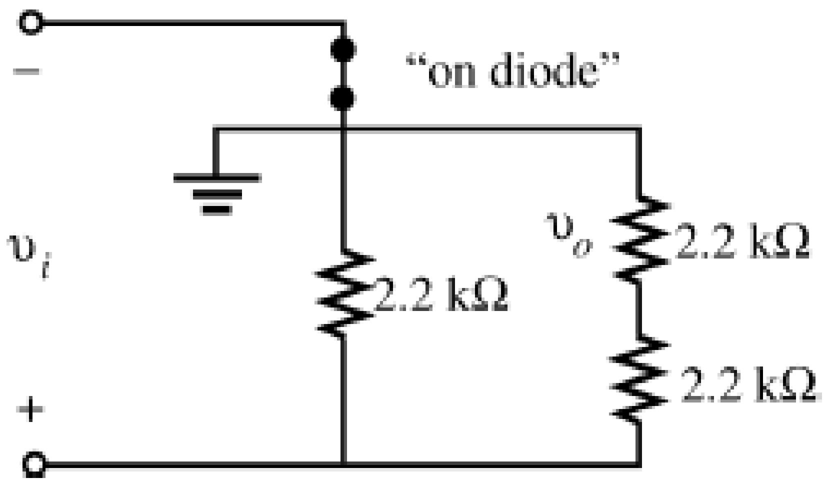
$$= \frac{1}{2}(V_{i_{\max}})$$

$$= \frac{1}{2}(100\ \text{V})$$

$$= 50\ \text{V}$$

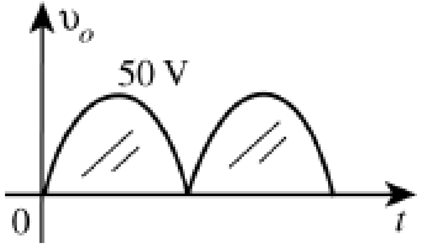
Numerical on Full Wave Rectifier: Bridge Rectifier

Negative half-cycle of υ_i :



Voltage-divider rule:

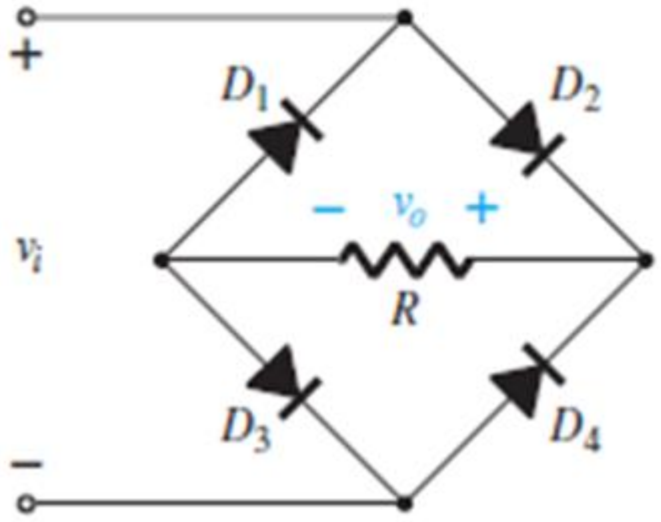
$$V_{o_{max}} = \frac{2.2\ \text{k}\Omega (V_{i_{max}})}{2.2\ \text{k}\Omega + 2.2\ \text{k}\Omega}$$
$$= \frac{1}{2}(V_{i_{max}})$$
$$= \frac{1}{2}(100\ \text{V})$$
$$= \mathbf{50\ V}$$



$$V_{dc} = 0.636 V_m = 0.636\ (50\ \text{V})$$
$$= \mathbf{31.8\ V}$$

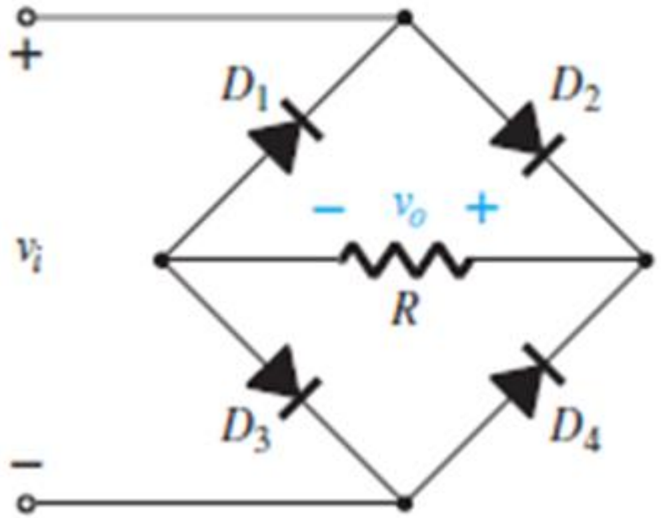
Numerical on Full Wave Rectifier: Bridge Rectifier

5. A full-wave bridge rectifier with a 120-V rms sinusoidal input has a load resistor of 1 kΩ.
   (a) If silicon diodes are employed, what is the dc voltage available at the load?
   (b) Determine the required PIV rating of each diode.
   (c) Find the maximum current through each diode during conduction.
   (d) What is the required power rating of each diode?



Numerical on Full Wave Rectifier: Bridge Rectifier

5. A full-wave bridge rectifier with a 120-V rms sinusoidal input has a load resistor of 1 kΩ.
   (a) If silicon diodes are employed, what is the dc voltage available at the load?
   (b) Determine the required PIV rating of each diode.
   (c) Find the maximum current through each diode during conduction.
   (d) What is the required power rating of each diode?



Numerical on Full Wave Rectifier: Bridge Rectifier

(a) $V_m = \sqrt{2}\,(120\text{ V}) = 169.7\text{ V}$

$$V_{L_m} = V_{i_m} - 2V_D$$

$$= 169.7\text{ V} - 2(0.7\text{ V}) = 169.7\text{ V} - 1.4\text{ V}$$

$$= 168.3\text{ V}$$

$$V_{dc} = 0.636(168.3\text{ V}) = \mathbf{107.04\text{ V}}$$

(b) PIV : $V_m - V_k = 169.7 - 0.7$ $= \mathbf{169\text{ V}}$

Numerical on Full Wave Rectifier: Bridge Rectifier

(c) $I_D(\max) = \dfrac{V_{L_m}}{R_L} = \dfrac{168.3\ \text{V}}{1\ \text{k}\Omega} = \mathbf{168.3\ mA}$

(d) $$\begin{aligned} P_{\max} = V_D I_D &= (0.7\ \text{V})I_{\max} \\ &= (0.7\ \text{V})(168.3\ \text{mA}) \\ &= \mathbf{117.81\ mW} \end{aligned}$$

Numerical on Full Wave Rectifier: Bridge Rectifier

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6. The input to a bridge rectifier is given through a 10 : 1 transformer from a supply of 230 Sin 314 t. If $R_L = 500\ \Omega$. Determine

DC load voltage

RMS load voltage

PIV across diodes

DC power delivered to the load

Numerical on Full Wave Rectifier: Bridge Rectifier

$$The\ primary\ voltage\ of\ transformer, V_1 = 230\ Sin\ 314\ t$$

$$Transformer\ turns\ ration, \frac{N_1}{N_2} = \frac{10}{1}$$

$$The\ secondary\ voltage\ of\ transformer, V_2 = \frac{N_2}{N_1}\ V_1 = \frac{1}{10}\ 230\ Sin\ 314\ t$$

$$V_2 = 23\ Sin\ 314\ t$$

$$V_2 = Vm\ Sin\ \omega t = 23\ Sin\ 314\ t$$

$$Therefore, Vm = 23\ V$$

Numerical on Full Wave Rectifier: Bridge Rectifier

$$DC\ load\ voltage, Vdc = \frac{2\,Vm}{\pi} = \frac{2 \times 23}{\pi}$$ = 14.64 V

$$RMS\ load\ voltage, Vrms = \frac{Vm}{\sqrt{2}} = \frac{23}{\sqrt{2}}$$ = 16.26

$$PIV\ across\ diodes, PIV \geq Vm \geq 23\,V$$

$$DC\ power\ delivered\ to\ the\ load, Pdc = Idc^2 \times R_L = \frac{Vdc^2}{R_L}$$ = 0.428 W

Numerical on Full Wave Rectifier: Centre Tap & Bridge Rectifier

7. In a two diode FWR using Si diodes, the RMS voltage across each half of the transformer secondary is 100V. The load resistance is 975 Ω Find (i) Average current (ii) Average output voltage (iii) PIV of diode.

   Ans: V_{dc} = 89.57V, I_{dc} = 91.8mA and PIV= 282.1V.

8. A Bridge rectifier with ideal diodes has an ac source of RMS value 220 V, 50Hz connected to the primary of transformer. If the load resistance is 200Ω and turns ratio of transformer is 4:1, find the dc output voltage, dc output current.

   Ans: V_{dc} = 49.6V, I_{dc} = 248mA .

Shunt Capacitor Filter

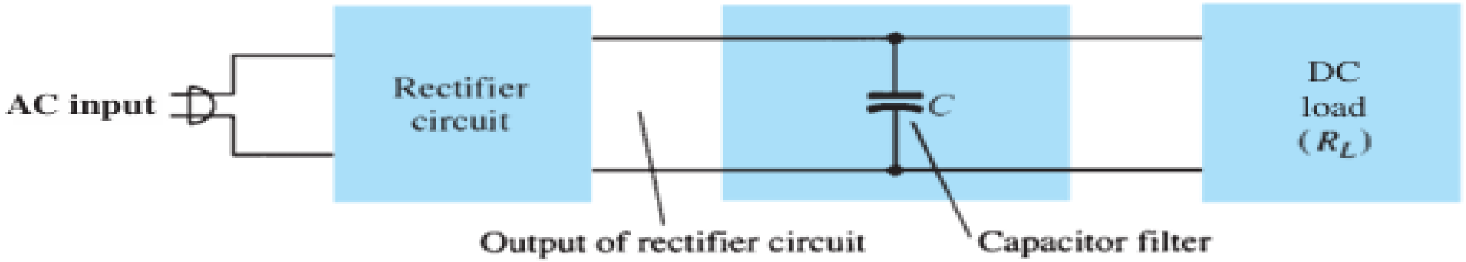
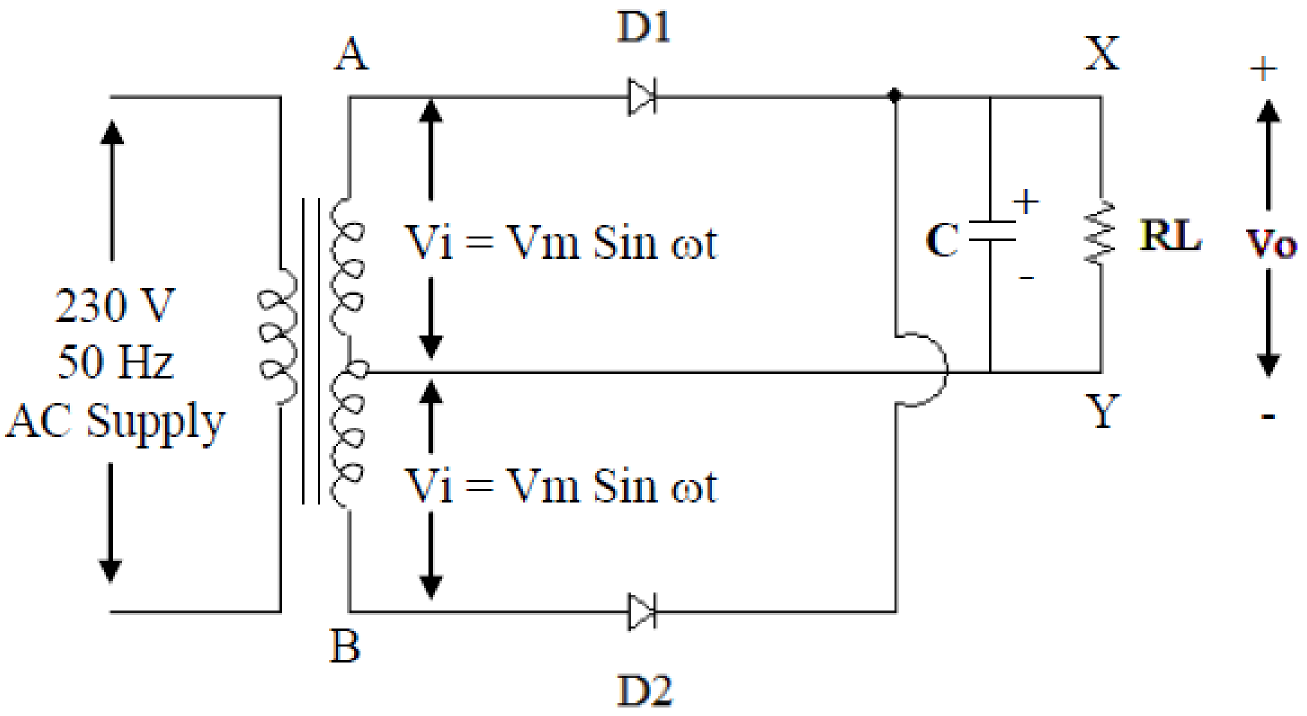


FIG. 15.3
Basic capacitor filter.

Filter is a circuit which converts pulsating DC to smooth DC. Since the reactance of capacitor and inductor depends on frequency, by connecting a capacitor in parallel with the load or by connecting an inductor in series with the load, the ac ripple present at the output of a rectifier can be reduced.

FWR with Shunt Capacitor Filter

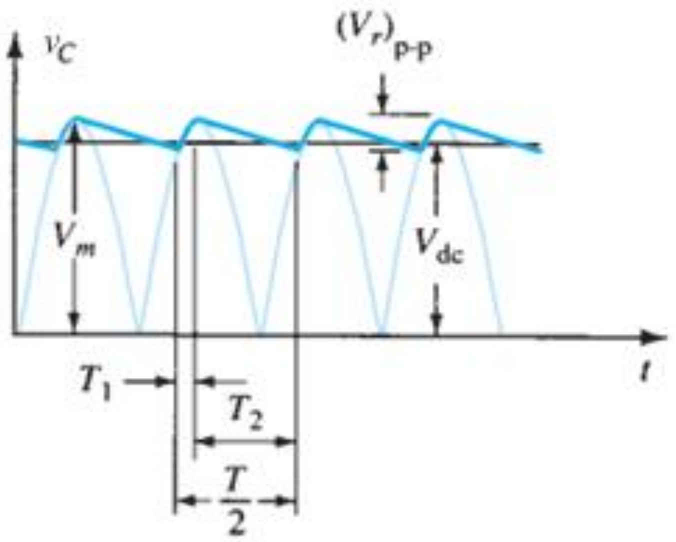


FWR with Shunt Capacitor Filter

Working

During positive half cycle the diode D1 is forward biased in centre tap full wave rectifier and diode D1 and D2 are forward biased in bridge rectifier. Hence the capacitor C will charge from 0 V towards the peak value of input Vm. When input voltage Vi reaches Vm the charge on capacitor will also be equal to Vm, hence the diodes will turn off (since both anode and cathode of diodes will be at same potential). Now the capacitor starts discharging through the load RL, if the load is very light (load resistance is very high and load current is low) the capacitor will discharge by a small amount, by that time next half cycle charges the capacitor back to Vm. Thus the output voltage remains almost constant.

Shunt Capacitor Filter



Capacitor filter: *Output voltage waveform*

Time T1 is the time during which diodes of the full-wave rectifier conduct, charging the capacitor up to the peak rectifier voltage Vm

Time T2 is the time interval during which the rectifier voltage drops below the peak voltage, and the capacitor discharges through the load.

Since the charge– discharge cycle occurs for each half-cycle for a full-wave rectifier, the period of the rectified wave form is T /2.

Shunt Capacitor Filter

Expression for ripple factor

$$\gamma = \frac{1}{4\sqrt{3}\, f\, C\, R_L}$$

$f \rightarrow$ *Frequency of input AC signal*

$C \rightarrow$ *Filter capacitor used*

$R_L \rightarrow$ *Load resistance*

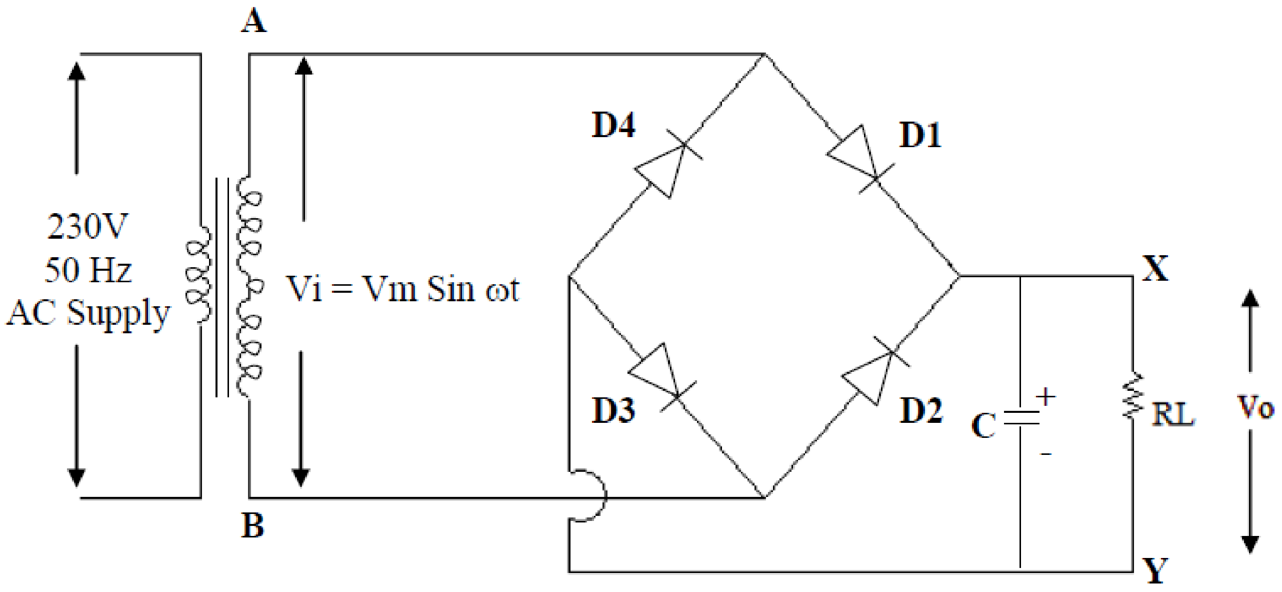
$$\gamma \propto \frac{1}{f} \quad \frac{1}{C} \quad \frac{1}{R_L}$$

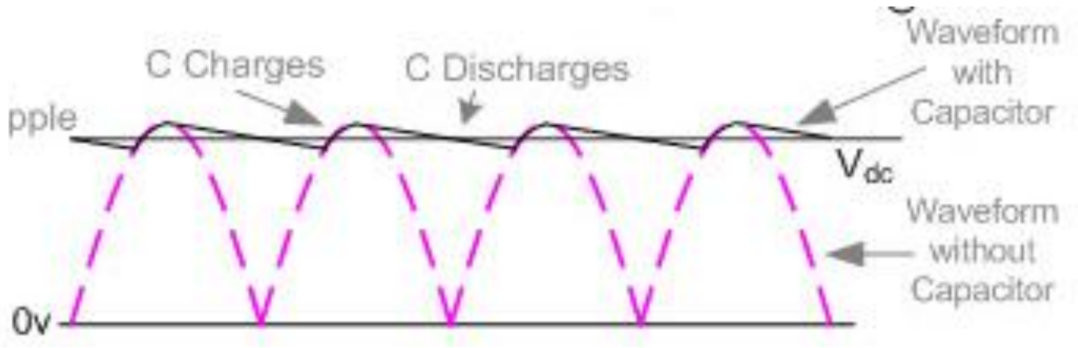
Since ripple is inversely proportional to frequency, capacitor and load resistance, the ripple can be minimized by using high value of C. (R_L and f are not in designer's hand)

$$\gamma = \frac{V_{r(rms)}}{V_{dc}}, V_{r(rms)} = \frac{I_{DC}}{4\sqrt{3} fc},$$

$$V_{dc} = V_m - \frac{I_{DC}}{4 fc}$$

Shunt Capacitor Filter for Bridge Rectifier

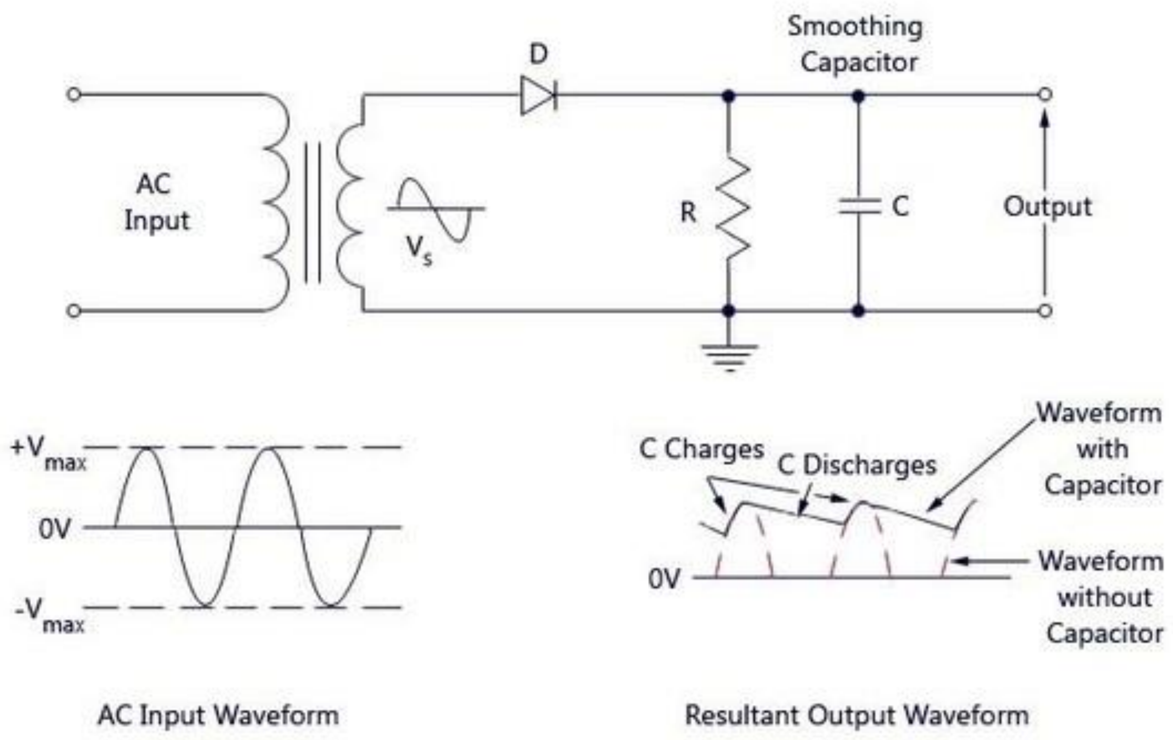


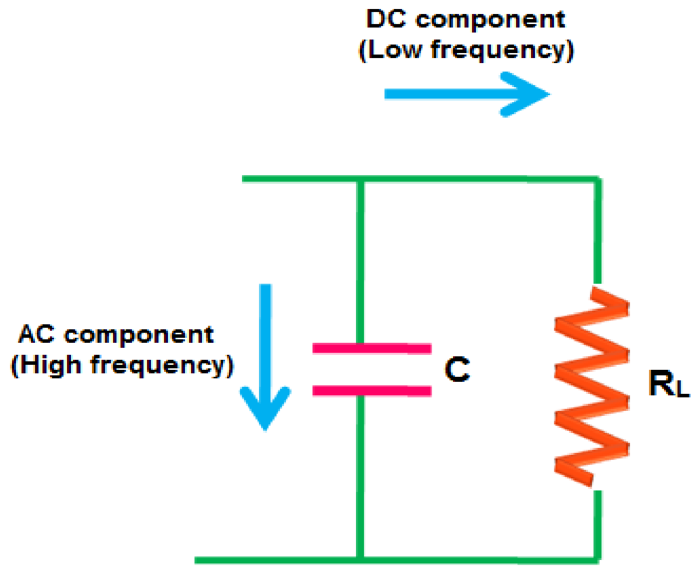


- ➢ AC components fluctuate with respect to time while the DC components remain constant with respect to time
- ➢ So the AC components present in the pulsating DC is an unwanted signal

Shunt Capacitor Filter for Half – Wave Rectifier

Capacitor C is connected in shunt/parallel with load resistor (R_L)





Shunt Capacitor Filter for Half – Wave Rectifier

Ripple Factor for Capacitor Filter of a Half Wave Rectifier is given by

Ripple Factor for a capacitor filter (HWR) = 1/ (2√3 f C R_L)

f – Frequency of AC input Signal
R_L – Value of Load resistor
C – Capacitance of the Shunt Capacitor

$$\gamma = \frac{V_{r(rms)}}{V_{dc}}, V_{r(rms)} = \frac{I_{DC}}{2\sqrt{3}fc},$$

$$V_{dc} = V_m - \frac{I_{DC}}{2fc}$$

Numerical on Shunt Capacitor Filter

1. A full wave rectifier with C filter is supplying a load of 500 Ω. If the ripple factor should not exceed 10 %, find the value of capacitor required. Assume input AC signal frequency is 50 Hz. What is the new value of ripple if capacitor of 500 μF is connected across the load?

Solution:

$Given\ \gamma = 10\ \% = 0.1\ and\ R_L = 500\Omega$

$$\gamma = \frac{1}{4\sqrt{3}\, f\, C\, R_L}$$

$$C = \frac{1}{4\sqrt{3}\, f\, \gamma R_L} = \frac{1}{4\sqrt{3} \times 50 \times 0.1 \times 500} = 57.73\ \mu F$$

$If\ a\ capacitor\ of\ 500\ \mu F\ is\ used\ the\ ripple\ factor\ is$

$$\gamma = \frac{1}{4\sqrt{3}\, f\, C\, R_L} = \frac{1}{4\sqrt{3} \times 50 \times 500 \times 10^{-6} \times 500} = 0.0115$$

Numerical on Shunt Capacitor Filter

2. In a full wave rectifier with C filter the output DC voltage is 10 V and load current is 10 mA. Calculate the value of capacitance required such that the output DC voltage will have ripple ≤ 0.001.

Solution:

$$R_L = \frac{Vdc}{Idc} = \frac{10}{10\ m} = 1\ K\Omega$$

$$Assume\ frequency\ of\ input\ AC\ signal, f = 50\ Hz$$

$$\gamma = \frac{1}{4\sqrt{3}\, f\, C\, R_L}$$

$$C = \frac{1}{4\sqrt{3}\, f\, \gamma R_L} = \frac{1}{4\sqrt{3} \times 50 \times 0.001 \times 1 \times 10^3} = 2886\ \mu F$$

Numerical on Shunt Capacitor Filter

3. Calculate the RMS value of the ripple voltage for the FWR in a 100µF Capacitor connected to a load drawing 50mA of current .What is the dc voltage at the output if the peak rectified output voltage is 30V and frequency is 50Hz. Also find the ripple factor

Solution:

$$\gamma = \frac{V_{r(rms)}}{V_{dc}}, V_{r(rms)} = \frac{I_{DC}}{4\sqrt{3}\, fc},$$

$$V_{dc} = V_m - \frac{I_{DC}}{4\, fc}$$

Given :

Idc= 50mA, f=50Hz, C=100µF

Therefore Vrms=1.4V

Vm= 30V

Therefore Vdc=27.5 V

Ripple factor=0.05

Numerical on Shunt Capacitor Filter

4. A Half wave rectifier with C filter is supplying a resistive load of 500Ω. If the load ripple content should not exceed 10% find the value of C required

Solution:

For a Half wave rectifier with C filter ,

Ripple Factor=1/2√3 f C R_L

0.10=1/{2√3*50*C*500}

C=0.115mF

Numerical on Shunt Capacitor Filter

5. A 100μF capacitor when used as a filter has 15V rms across it with a load resistor of 2.5KΩ. If the filter is the full wave and supply frequency is 50Hz, what is the percentage of ripple factor in the output?

Solution:

For a full wave rectifier with C filter ,

Ripple factor, $\Upsilon = 1/4\sqrt{3}\ f\ C\ R_L$

$=1/4\sqrt{3}*50*100*10^{-6}*2.5*10^{-3}$

=0.01154.

So, ripple factor is 1.154%

Numerical on Shunt Capacitor Filter

6. A full wave rectifier uses a capacitor filter with 500µF capacitor and provides a load current of 200mA at 8% ripple. Calculate the dc voltage and the value of peak rectified voltage?

Solution:

The ripple factor for Full Wave Rectifier with C filter

$\Upsilon = 1/\ 4\sqrt{3}\ f\,C\,RL$ substituting $RL = Vdc/Idc$

$\Upsilon = Idc/\ 4\sqrt{3}\ f\,C\,Vdc$

after re-arranging

$V_{DC} = 200*10^{-3}/\ 4\sqrt{3}\ *50*500*10^{-6}\ *0.08$

$V_{DC} = 14.43V$

We know, $V_m = V_{dc} + I_{dc}/4fC$

$= 14.43 + \{200*\ 10^{-3} / \{\ 4*50*500*10^{-6}\ \}$

$= 14.43 + 2 = 16.43V$

$V_m = 16.43V$

UNIT - II: Zener Diode

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- Heavily Doped PN-Junction Device Specially Designed to operate under breakdown region

- Zener Diode under forward Bias condition works like a normal semiconductor diode

- Zener Diode under reverse bias condition acts like Voltage regulator

- Zener diodes are usually heavily doped diodes hence the depletion layer is very narrow. When the reverse voltage across the junction is increased the electric field across the depletion layer becomes high so that electrons are pulled out of covalent bonds resulting in a sudden rise in current which is known as zener breakdown.

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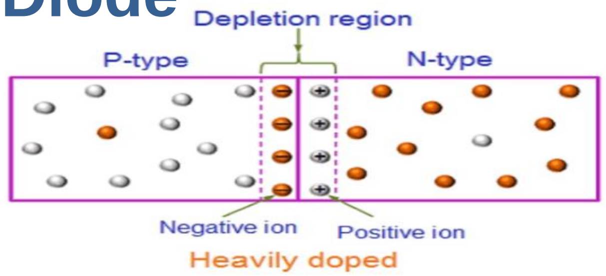
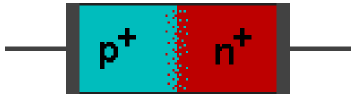
Structure of Zener Diode





Symbol of Zener Diode

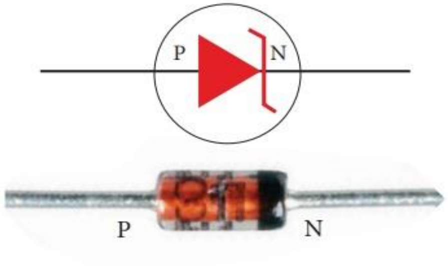


Figure (a) Zener diode and its symbol
(The black colour ring denotes the negative terminal of the Zener diode)

V-I Characteristics of Zener Diode

V-I Characteristics of Zener Diode in Forward Bias Condition

V-I Characteristics of Zener Diode in Reverse Bias Condition

UNIT - II: Zener Diode Characteristics

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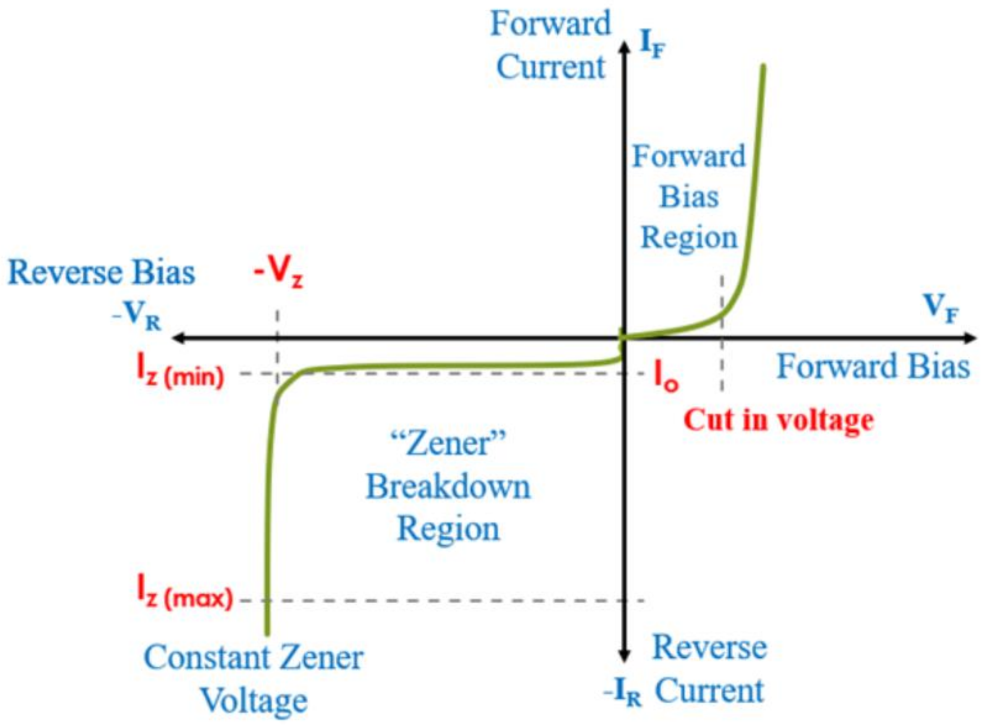
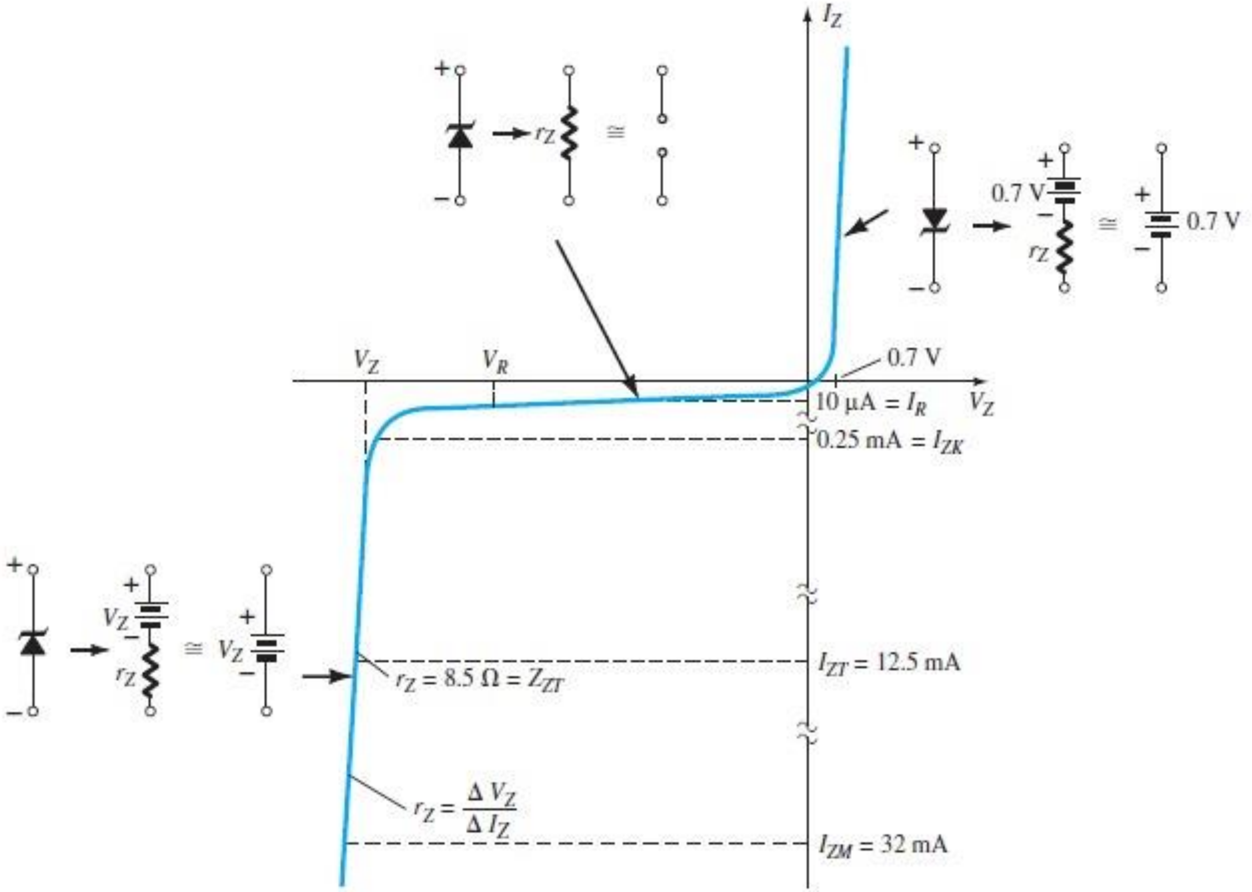
V-I Characteristics

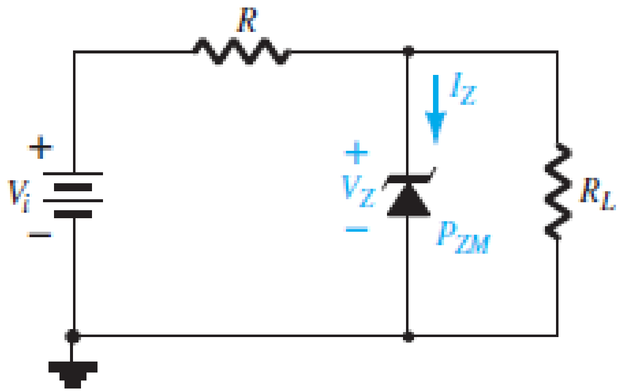


Graph showing equivalent circuit in each of the regions

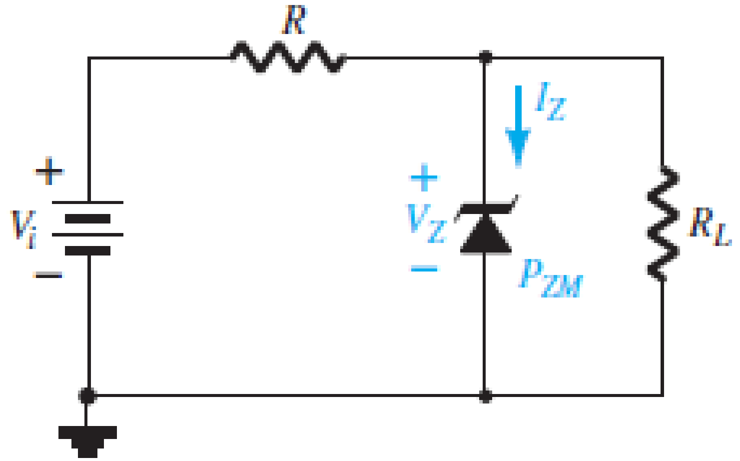


Conditions required to operate Zener Diode as Voltage Regulator

- Zener Diode should be in Reverse Biased Condition
- Vin should be Greater than Vz
- Iz should be greater than Izmin
- Iz should be less than or equal to Izmax



UNIT - II: Zener Diode as Voltage Regulator



Different operating conditions of Zener Regulator .

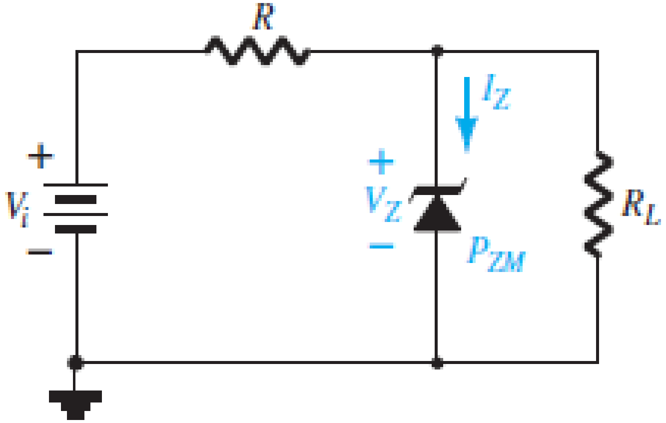
(i) Fixed quantities, (Vi and R are fixed)

(ii) Fixed supply voltage and a variable load,(Fixed Vi and variable RL)

(iii) Fixed load and a variable supply.(Fixed RL and Variable Vi)

(iv) Variable Supply and Variable Load. (Variable Vi and Variable RL)

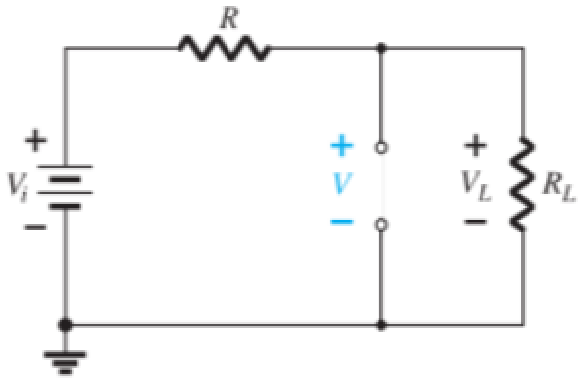
CASE-1: Fixed Vi and fixed R_L Voltage Regulator



The analysis can fundamentally be broken down into two steps.

1. Determine the state of the Zener diode by removing it from the network and calculating the voltage across the resulting open circuit

$$V = V_L = \frac{R_L V_i}{R + R_L}$$



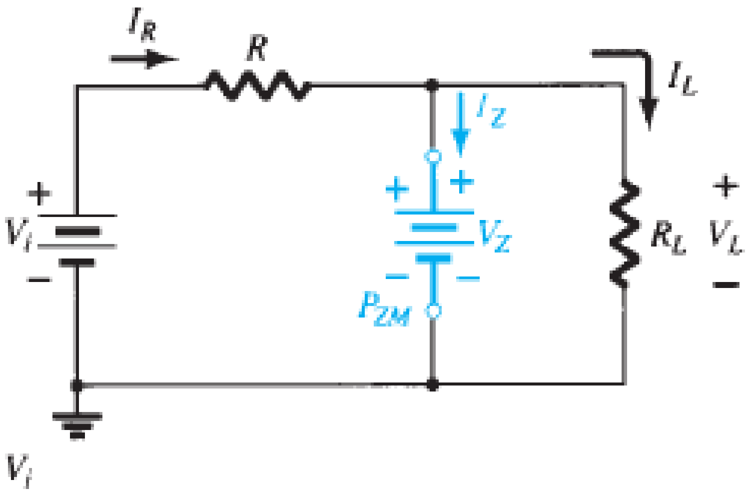
If $V \geq V_Z$, the Zener diode is on, and the appropriate equivalent model can be substituted.
If $V < V_Z$, the diode is off, and the open-circuit equivalence is substituted.

CASE-1: Fixed Vi and fixed R_L Voltage Regulator

Conclusion:

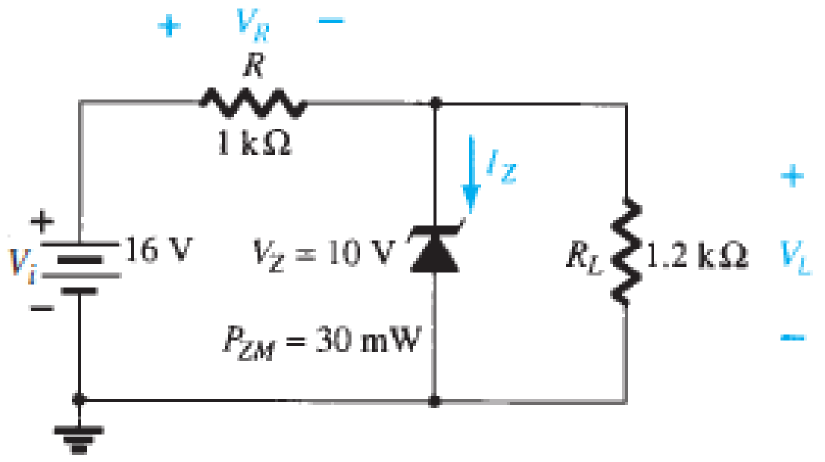
If the Zener diode is in the “on” state, the voltage across the diode is not *V volts.*

The Zener diode will turn on as soon as the voltage across the Zener diode is VZ volts.
It will then “lock in” at this level and never reach the higher level of V volts.



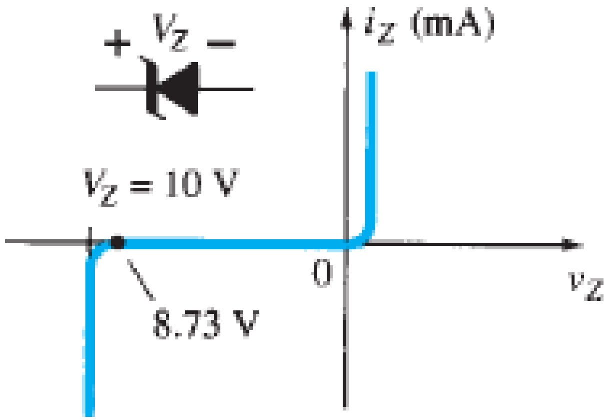
CASE-1: Fixed Vi and fixed R_L Voltage Regulator

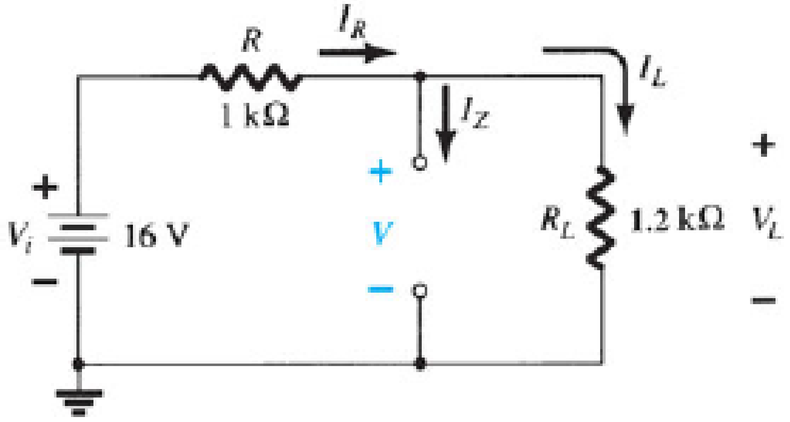
1. For the Zener diode network of Fig,
(i) Determine V_L , V_R , I_Z , and P_Z .
(ii) Repeat part (a) with $R_L = 3K\Omega$.



Solution (i):

$$V = \frac{R_L V_i}{R + R_L} = \frac{1.2\ \text{k}\Omega(16\ \text{V})}{1\ \text{k}\Omega + 1.2\ \text{k}\Omega} = 8.73\ \text{V}$$

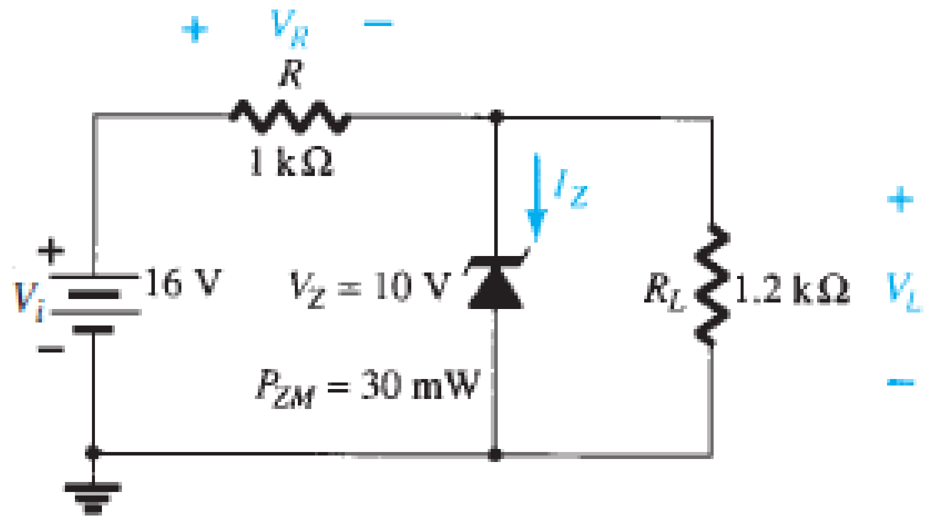




CASE-1: Fixed Vi and fixed R_L Voltage Regulator

Solution (i):

$$V_L = V = 8.73\text{ V}$$
$$V_R = V_i - V_L = 16\text{ V} - 8.73\text{ V} = 7.27\text{ V}$$
$$I_Z = 0\text{ A}$$
$$P_Z = V_Z I_Z = V_Z(0\text{ A}) = 0\text{ W}$$



CASE-1: Fixed Vi and fixed R_L Voltage Regulator

Solution: (ii)

$$V = \frac{R_L V_i}{R + R_L} = \frac{3\,\text{k}\Omega(16\text{ V})}{1\,\text{k}\Omega + 3\,\text{k}\Omega} = 12\text{ V}$$

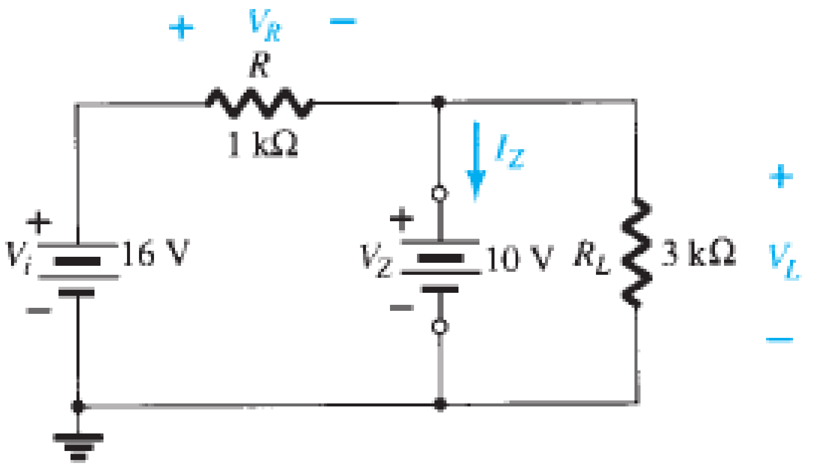
$$V_L = V_Z = \mathbf{10\ V}$$

$$V_R = V_i - V_L = 16\text{ V} - 10\text{ V} = \mathbf{6\ V}$$

$$I_L = \frac{V_L}{R_L} = \frac{10\text{ V}}{3\,\text{k}\Omega} = 3.33\text{ mA}$$

$$I_R = \frac{V_R}{R} = \frac{6\text{ V}}{1\,\text{k}\Omega} = 6\text{ mA}$$

$$I_Z = I_R - I_L\ [\text{Eq. (2.18)}]$$
$$= 6\text{ mA} - 3.33\text{ mA}$$
$$= \mathbf{2.67\ mA}$$



The power dissipated is

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

which is less than the specified $P_{ZM} = 30$ mW.

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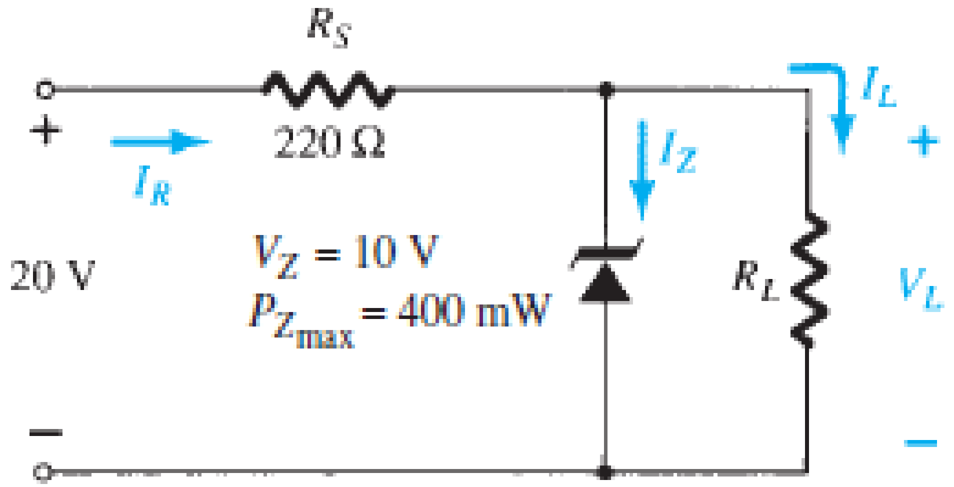
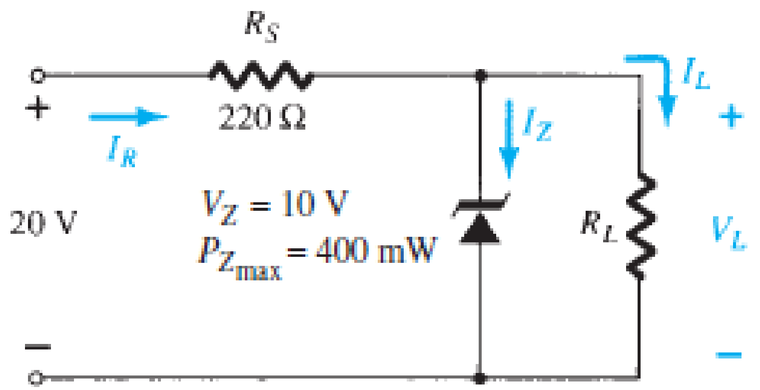
CASE-1: Fixed Vi and fixed R_L Voltage Regulator

2. (a) Determine V_L , I_L , I_Z , and I_R *for the network of Fig. if* R_L *=180 ohm .*
(b) Repeat part (a) if R_L = *470 ohm .*



CASE-1: Fixed Vi and fixed R_L Voltage Regulator



Solution a:

In the absence of the Zener diode

$$V_L = \frac{180\ \Omega(20\ \text{V})}{180\ \Omega + 220\ \Omega} = 9\ \text{V}$$

$V_L = 9\ \text{V} < V_Z = 10\ \text{V}$ and diode non-conducting

Therefore, $I_L = I_R = \dfrac{20\ \text{V}}{220\ \Omega + 180\ \Omega} = \mathbf{50\ mA}$

with $I_Z = \mathbf{0\ mA}$
and $V_L = \mathbf{9\ V}$

Solution b:

In the absence of the Zener diode

$$V_L = \frac{470\ \Omega(20\ \text{V})}{470\ \Omega + 220\ \Omega} = 13.62\ \text{V}$$

$V_L = 13.62\ \text{V} > V_Z = 10\ \text{V}$ and Zener diode "on"

Therefore, $V_L = \mathbf{10\ V}$ and $V_{R_s} = 10\ \text{V}$

$I_{R_s} = V_{R_s} / R_s = 10\ \text{V}/220\ \Omega = \mathbf{45.45\ mA}$

$I_L = V_L/R_L = 10\ \text{V}/470\ \Omega = \mathbf{21.28\ mA}$

and $I_Z = I_{R_s} - I_L = 45.45\ \text{mA} - 21.28\ \text{mA} = \mathbf{24.17\ mA}$

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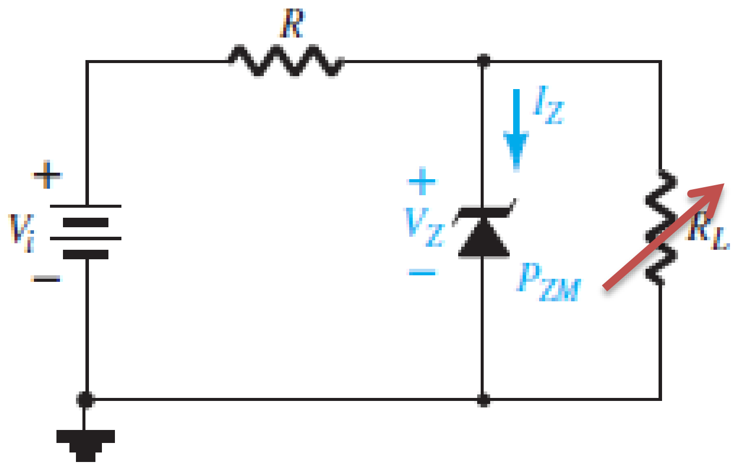
CASE-2: Fixed supply voltage and a variable load

Conditions for R_L to Keep the Zener currnet I_Z in the operating limit i.e $I_{Zmin} \leq I_Z < I_{Zmax}$

1: Condition for R_{Lmin} :



$$\mathrm{I_L} = \mathrm{I_R} - \mathrm{I_Z}$$

$$R_L = \frac{V_Z}{I_L}$$

R_L is Minimum when I_L is Maximum

$$\mathrm{I_{Lmax}} = \mathrm{I_R} - \mathrm{I_{Zmin}}$$

where $I_R = \dfrac{V_i - V_Z}{R}$

$$R_{Lmin} = \frac{V_Z}{I_{Lmax}}$$

If I_{Zmin} = 0 then I_{Lmax} = I_R

hence, $R_{Lmin} = \dfrac{V_Z}{I_R} = \dfrac{V_Z R}{V_i - V_Z}$

CASE-2: Fixed supply voltage and a variable load

Conditions for R_L to Keep the Zener currnet I_Z in the operating limit i.e

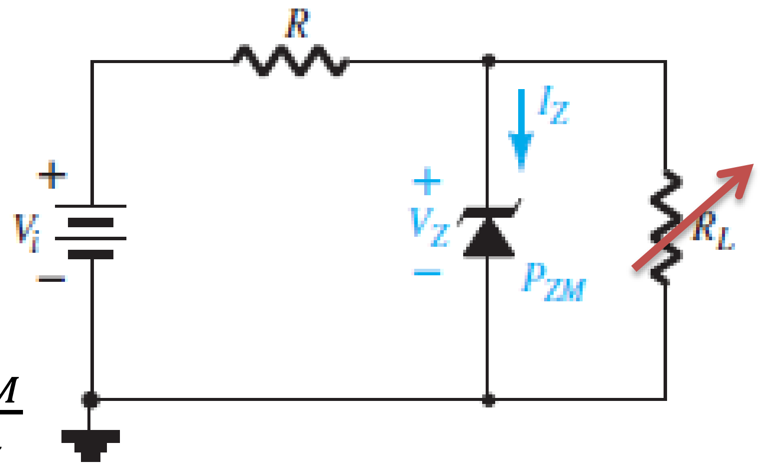
$$I_{Zmin} \leq I_Z < I_{Zmax}$$

2: Condition for R_{Lmax} :

$$I_L = I_R - I_Z$$

$$R_L = \frac{V_Z}{I_L}$$

R_L is Maximum when I_L is Minimum



$$I_{Lmin} = I_R - I_{Zmax} \quad \text{where} \quad I_R = \frac{V_i - V_z}{R} \text{ and } I_{Zmax} = \frac{P_{ZM}}{V_Z}$$

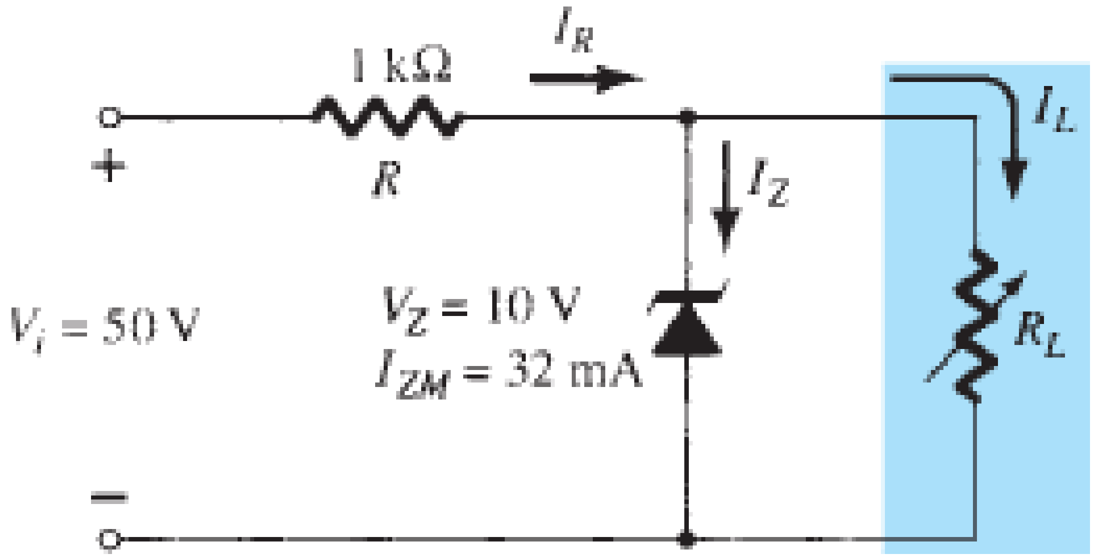
$$R_{Lmax} = \frac{V_Z}{I_{Lmin}}$$

CASE-2: Fixed supply voltage and a variable load

3. For the network of Fig

(i) Determine the range of R_L and I_L that will result in V_{RL} being maintained at 10 V. Given I_{Zmin} = 1mA.

(ii) Determine the maximum wattage rating of the diode.



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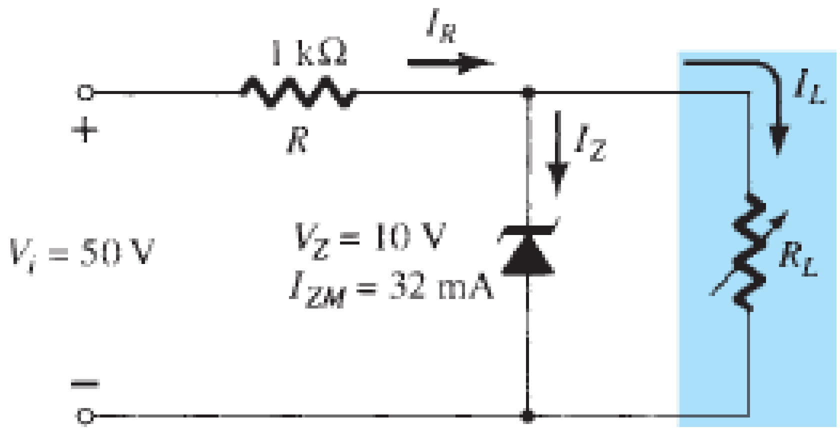
CASE-2: Fixed supply voltage and a variable load



(i) $$I_R = \frac{V_i - V_Z}{R} = \frac{50-10}{1\text{k}\Omega} = 40mA$$

$$\mathrm{I_{Lmax}} = \mathrm{I_R} - \mathrm{I_{Zmin}} = 40\text{mA} - 1\text{mA} = 39\text{mA}$$

$$\mathrm{I_{Lmin}} = \mathrm{I_R} - \mathrm{I_{Zmax}} = 40\text{mA} - 32\text{mA} = 8\text{mA}$$

$$R_{Lmax} = \frac{V_Z}{I_{Lmin}} = \frac{10}{8mA} = 1.25K\Omega$$

$$R_{Lmin} = \frac{V_Z}{I_{Lmax}} = \frac{10}{39mA} = 256.41\ \Omega$$

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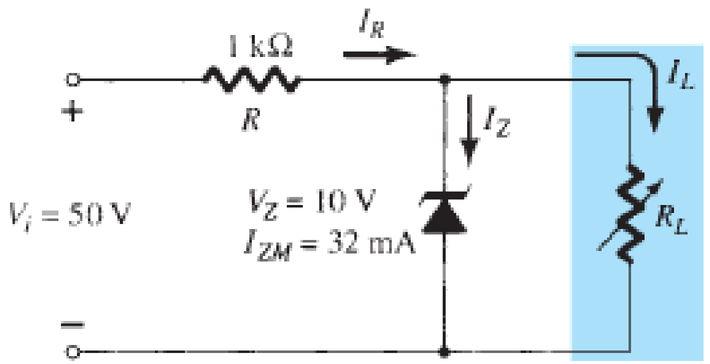
CASE-2: Fixed supply voltage and a variable load

3. For the network of Fig
(ii) Determine the maximum wattage rating of the diode.

(ii) Maximum Watage $P_{Zmax} = Vz * I_{zmax} = 320mW$



CASE-2: Fixed supply voltage and a variable load

4. Determine the value of R_L that will establish maximum power conditions for the Zener diode. Determine the minimum value of R_L to ensure that the Zener diode is in the "on" state.

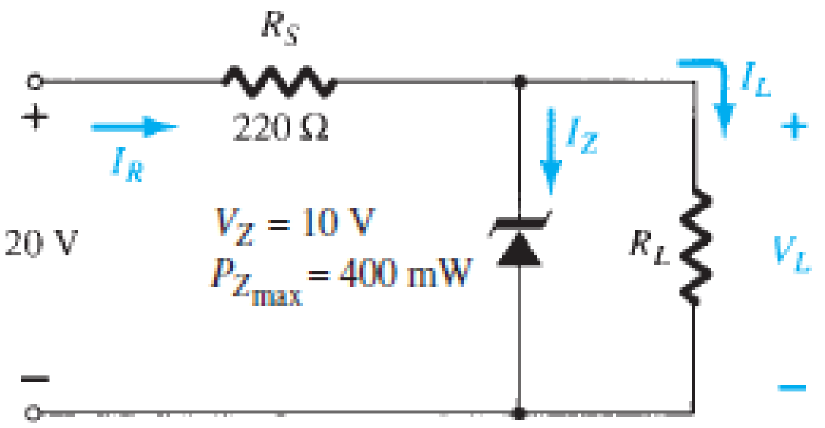
$$P_{Z_{max}} = 400 \text{ mW} = V_Z I_Z = (10 \text{ V})(I_Z)$$

$$I_Z = \frac{400 \text{ mW}}{10 \text{ V}} = 40 \text{ mA}$$

$$I_{L_{min}} = I_{R_s} - I_{Z_{max}} = 45.45 \text{ mA} - 40 \text{ mA} = 5.45 \text{ mA}$$

$$R_L = \frac{V_L}{I_{L_{min}}} = \frac{10 \text{ V}}{5.45 \text{ mA}} = \mathbf{1{,}834.86\ \Omega}$$

Large R_L reduces I_L and forces more of I_{R_s} to pass through Zener diode.



If $I_{Zmin} = 0$ then $I_{Lmax} = I_R$

hence, $$R_{Lmin} = \frac{V_Z}{I_R} = \frac{V_Z R}{V_i - V_Z}$$

Here R = Rs = 220 Ω

R_{Lmin} = 10 (220)/(20-10) = 220Ω

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CASE-3: Fixed R_L , Variable Vi

Conditions for Vi to Keep the Zener current I_Z in the operating limit i.e $I_{Zmin} \leq I_Z < I_{Zmax}$

1: Condition for Vi_{min} :

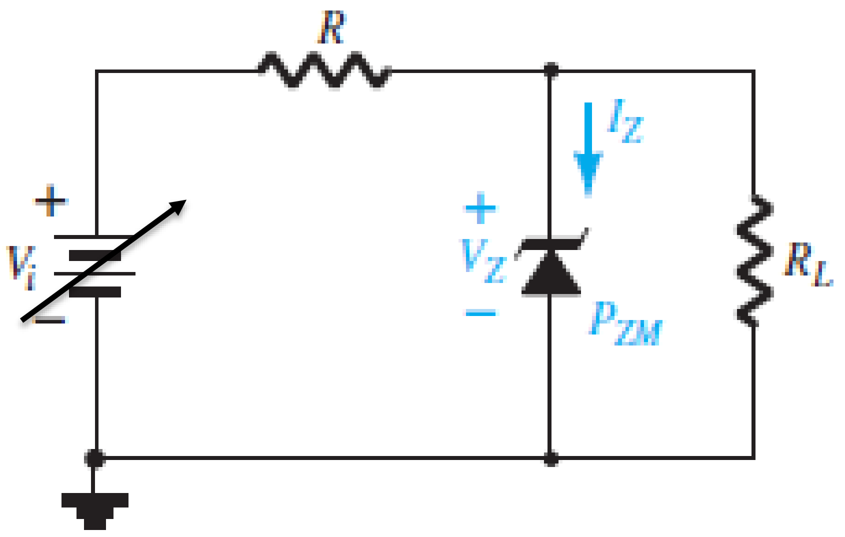
$$I_R = I_Z + I_L$$

$$I_{Rmin} = I_{Zmin} + I_L$$

$$I_{Rmin} = \frac{V_{imin} - V_z}{R}$$

$$V_{imin} = V_Z + I_{Rmin} R$$

If $I_{Zmin} = 0$; $then\ I_{Rmin} = I_L; V_{imin} = V_Z + I_L R = \frac{V_Z(R_L+R)}{R_L}$



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CASE-3: Fixed R_L , Variable Vi

Conditions for Vi to Keep the Zener currnet I_Z in the operating limit i.e $I_{Zmin} \leq I_Z < I_{Zmax}$

2: Condition for Vi_{max} :

$$\mathrm{I_R = I_Z + I_L}$$

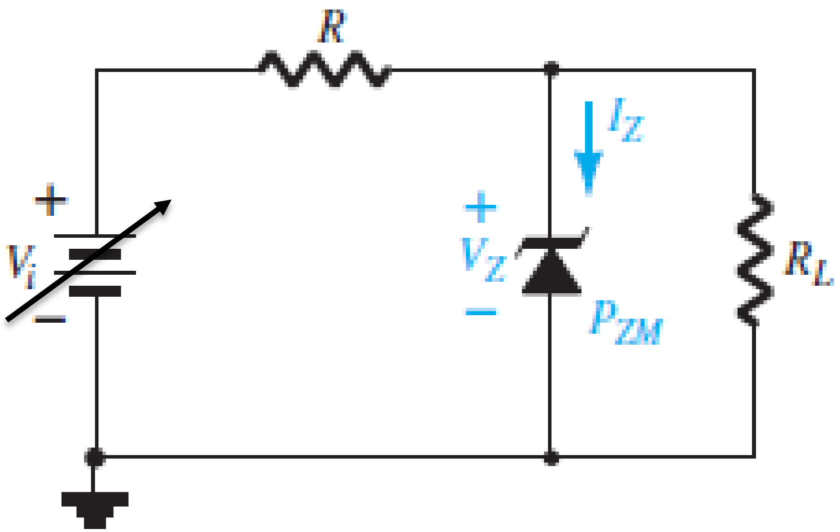
$$\mathrm{I_{Rmax} = I_{Zmax} + I_L}$$

$$I_L = \frac{V_Z}{R_L}$$

$$I_{Rmax} = \frac{V_{imax} - V_z}{R}$$

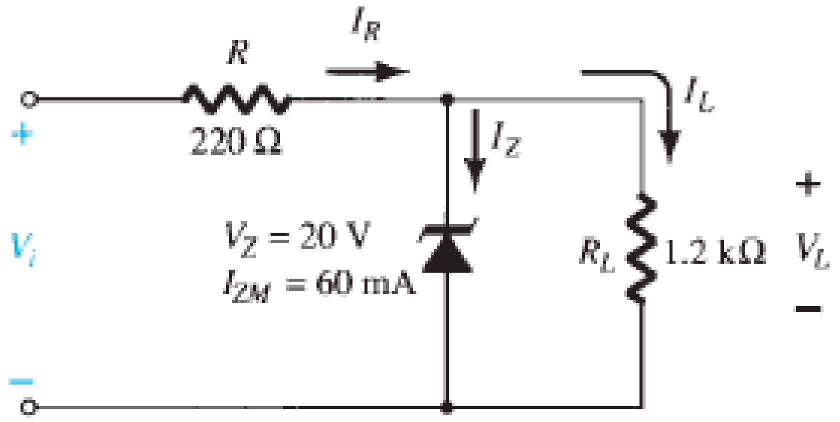
$$I_{Zmax} = \frac{P_{ZM}}{V_Z}$$

$$V_{imax} = V_Z + I_{Rmax}R$$



CASE-3: Fixed R_L , Variable Vi

5. Determine the range of values of *Vi that will maintain the Zener diode of* Fig. in the "on" state. Given I_{Zmin} = 2mA



$$V_{imin} = V_Z + I_{Rmin}R$$

$$\mathrm{I_{Rmin}} = \mathrm{I_{Zmin}} + \mathrm{I_L}$$

$$I_L = \frac{V_Z}{R_L} = \frac{20}{1.2K\Omega} = 16.67mA$$

$$I_{Rmin} = 2mA + 16.67mA = 18.67mA$$

$$V_{imin} = 20 + 18.67mA * 220\Omega = 24.107V$$

$$V_{imax} = V_Z + I_{Rmax}R$$

$$\mathrm{I_{Rmax}} = \mathrm{I_{Zmax}} + \mathrm{I_L}$$

$$I_{Rmax} = 60mA + 16.67mA = 76.67mA$$

$$V_{imax} = 20 + 76.67mA * 220\Omega = 36.86V$$

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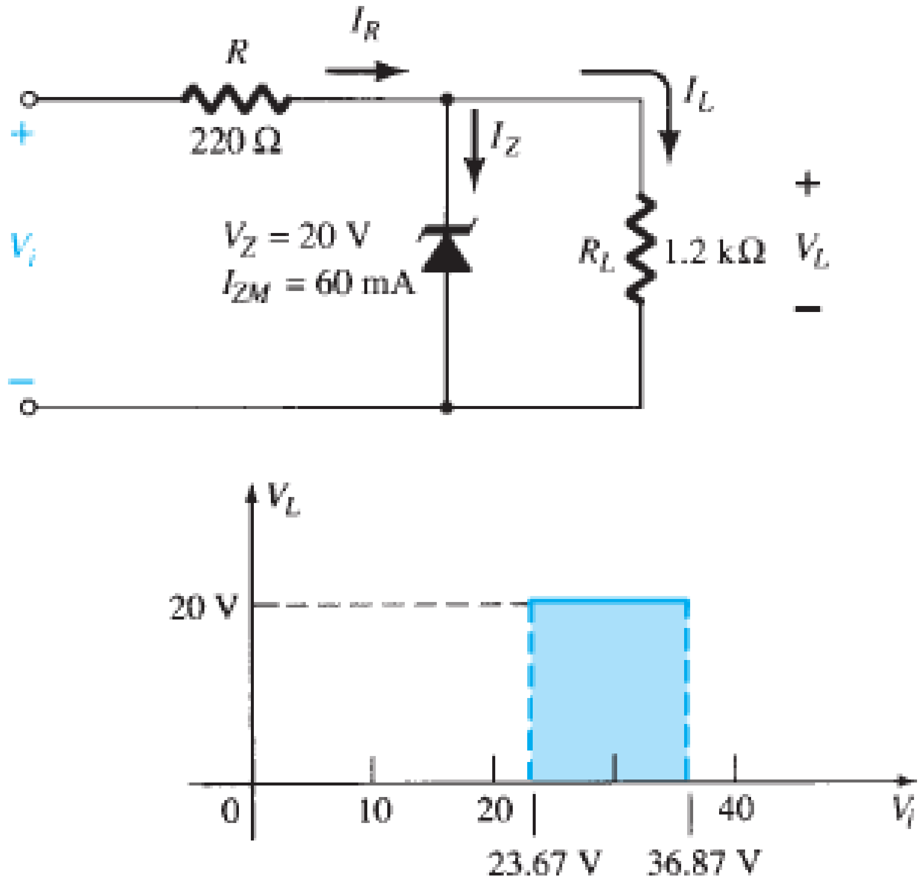
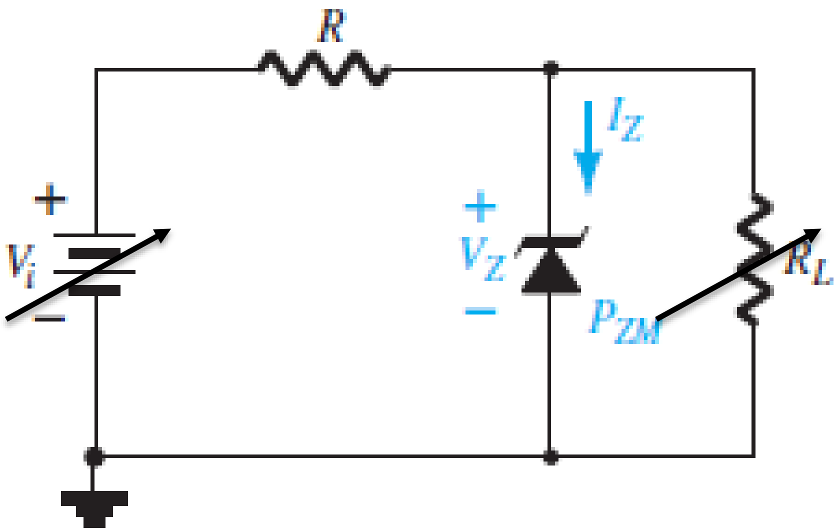
CASE-3: Fixed R_L , Variable V_i



CASE-4: Variable supply voltage and a variable load

Worst case conditions for Zener Diode:

1. For the diode to enter into to the breakdown region, the necessary condition is $I_Z \geq I_{Zmin}$.



I_Z can become less than I_{Zmin} when

(i) I_L increases or R_L decreases.
(ii) R increases or I_R decreases.
(iii) Vin decreases.

Hence the value for Rmax to ensure $I_Z \geq I_{Zmin}$ is

$$R_{max} = \frac{V_{imin} - V_Z}{I_{Zmin} + I_{Lmax}}$$

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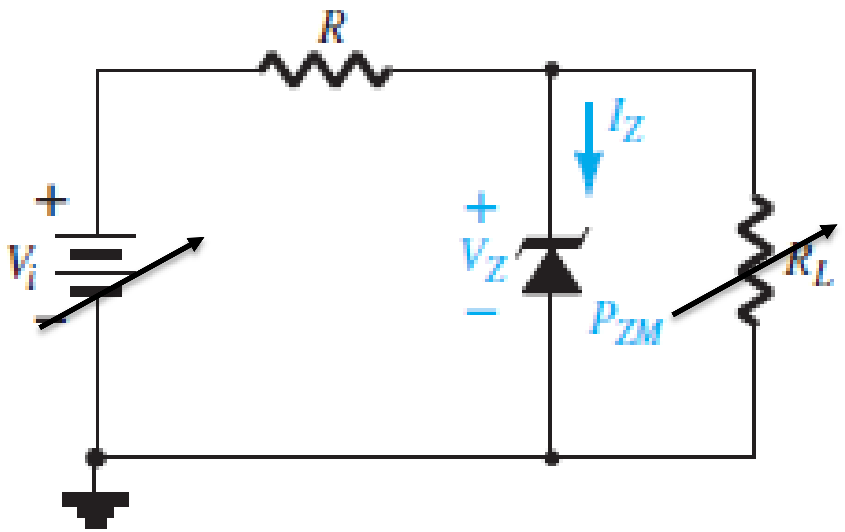
CASE-4: Variable supply voltage and a variable load

Worst case conditions for Zener Diode:

2. *The upper limit for the Zener current is* $I_Z < I_{Zmax}$.



I_Z can become greater than I_{Zmax} when

(i) I_L decreases or R_L increases.
(ii) R decreases or I_R increases.
(iii) Vin increases.

Hence the value for Rmin is to ensure $I_Z < I_{Zmax}$ is

$$R_{min} = \frac{V_{imax} - V_Z}{I_{Zmax} + I_{Lmin}}$$

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CASE-4: Variable supply voltage and a variable load

6. Design a Zener voltage regulator that maintains Vo at 10V for input voltage variation of 20V$\pm$10% and load current variation of 30mA $\pm$20%. Given $I_{Zmin} = 2mA \ and \ P_{Zmax} = 0.5W$

Vimin = 20 V - 2V = 18V

Vimax = 20V + 2V = 22 V

I_{Lmin} = 30mA – 6mA = 24mA

I_{Lmax} = 30mA + 6mA = 36mA

$$R_{max} = \frac{V_{imin} - V_Z}{I_{Zmin} + I_{Lmax}} = \frac{18 - 10}{2mA + 36mA} = 210.5\ \Omega$$

$$R_{min} = \frac{V_{imax} - V_Z}{I_{Zmax} + I_{Lmin}} = \frac{22 - 10}{50mA + 24mA} = 162.16\ \Omega$$

$162.16\Omega \leq \text{R} \leq 210.52\ \Omega$

THANK YOU

Department of Electronics and Communication