NANYANG TECHNOLOGICAL UNIVERSITY

INTEGRATED ELECTRONICS

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Topics

1. **Power Supplies**
2. **Bias Circuits**
3. **Operational Amplifiers**
4. **Applications of Operational Amplifiers**

Reference Textbooks

1. Sedra and Smith, *Microelectronic Circuits*, 5th Edition, Oxford University Press, 2004.

2. Gray, Hurst, Lewis and Meyer, *Analysis and Design of Analogue Integrated Circuits*, 4th Edition, John Wiley & Sons, 2001.

3. Franco S, *Design with Operational Amplifiers and Analog Integrated Circuits*, 3rd Edition, McGraw-Hill, 2002.

Power Supplies

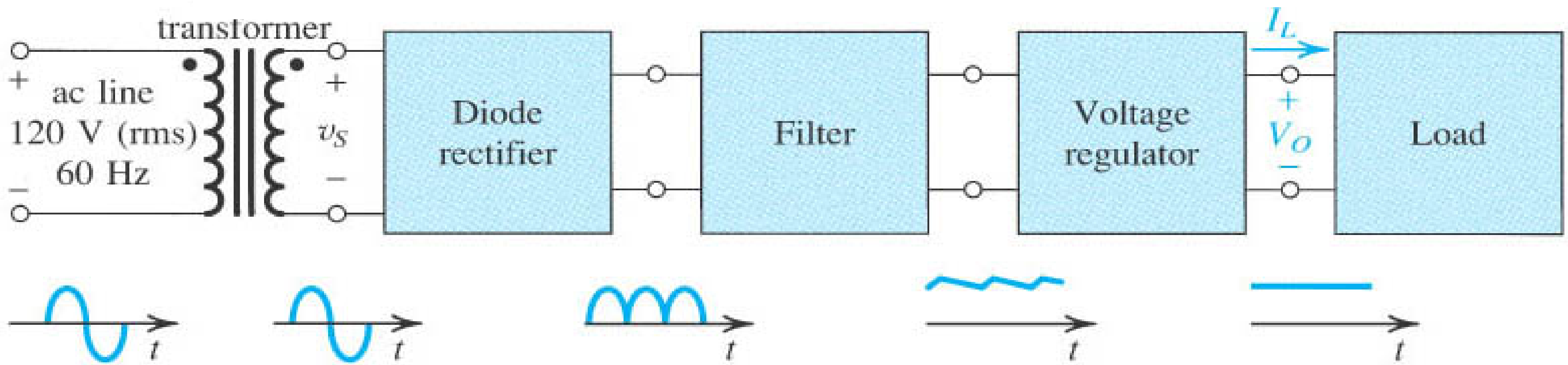
1. **Introduction**
2. **Rectifiers**

   Half-wave, full-wave, and full-wave bridge rectifiers
3. **Capacitor filters**
4. **Voltage regulators**

   Zener-diode circuits and series voltage regulators

Introduction

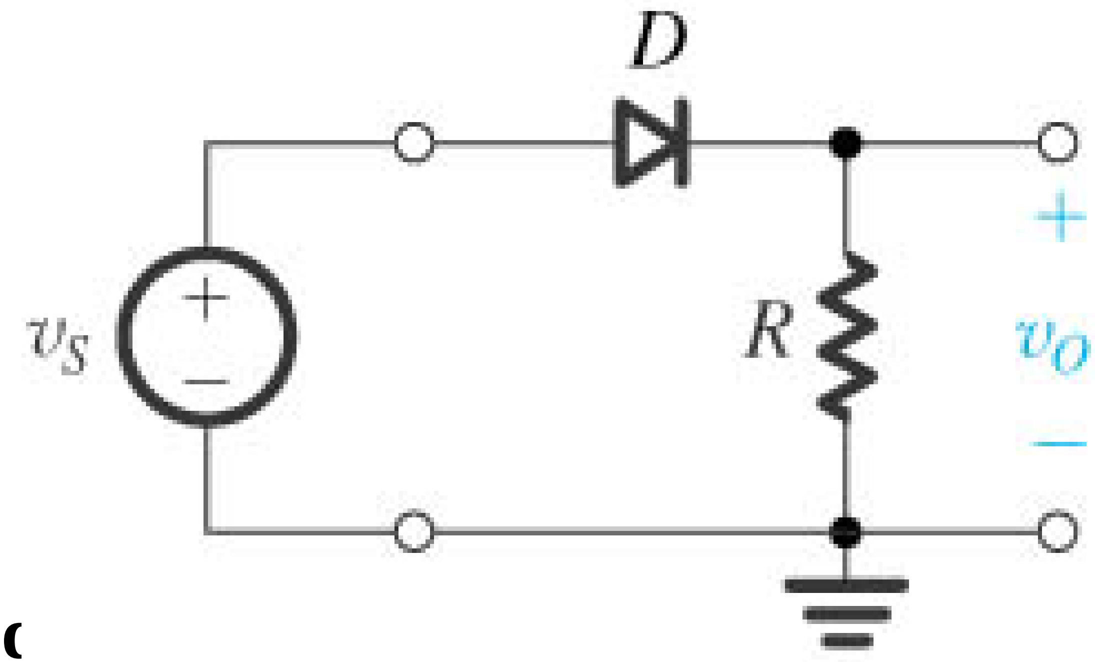
The design of power supply depends on the target application, ranging from providing half-wave rectified output for battery chargers to highly regulated output for precision instruments



Rectifier converts ac to pulsating dc.
Filter smoothes pulsating voltage .
Regulator maintains constant output voltage, under variations in line voltage and current.

Half-Wave Rectifier

Let the voltage drop of the conducting diode be V_{D0} (normally ~0.7V). Diode does not conduct until voltage across it is greater than V_{D0} (in this figure, the V_{D0} is assumec zero).



(a)

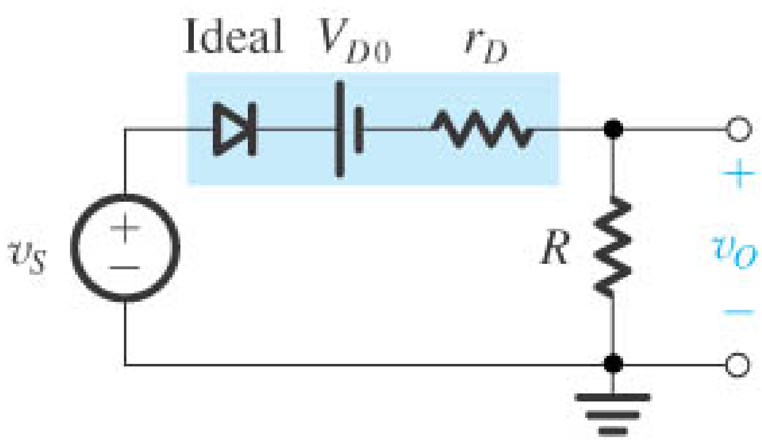
Half-Wave Rectifier

When $v_S < V_{D0}$, diode is off and v_O=0.

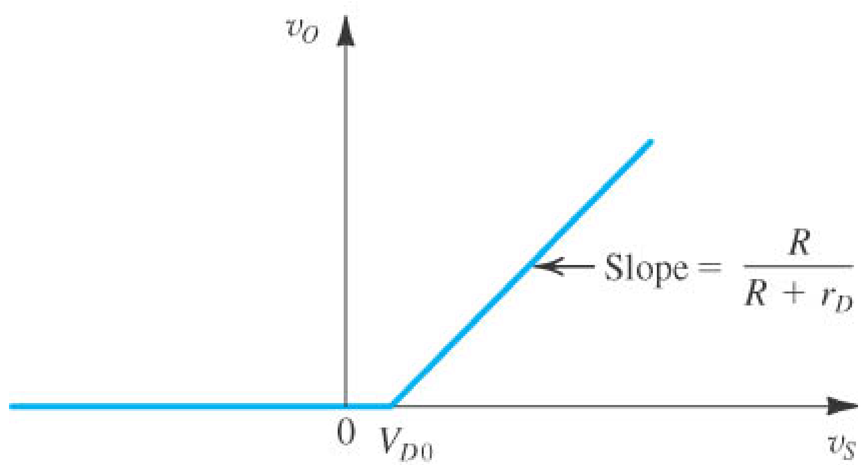
When $v_S \geq V_{D0}$, diode conducts and

$$v_O = \frac{R}{R+r_D} v_S - \frac{R}{R+r_D} V_{D0}$$

$$\approx v_S - V_{D0} \qquad (r_D << R)$$



(b)

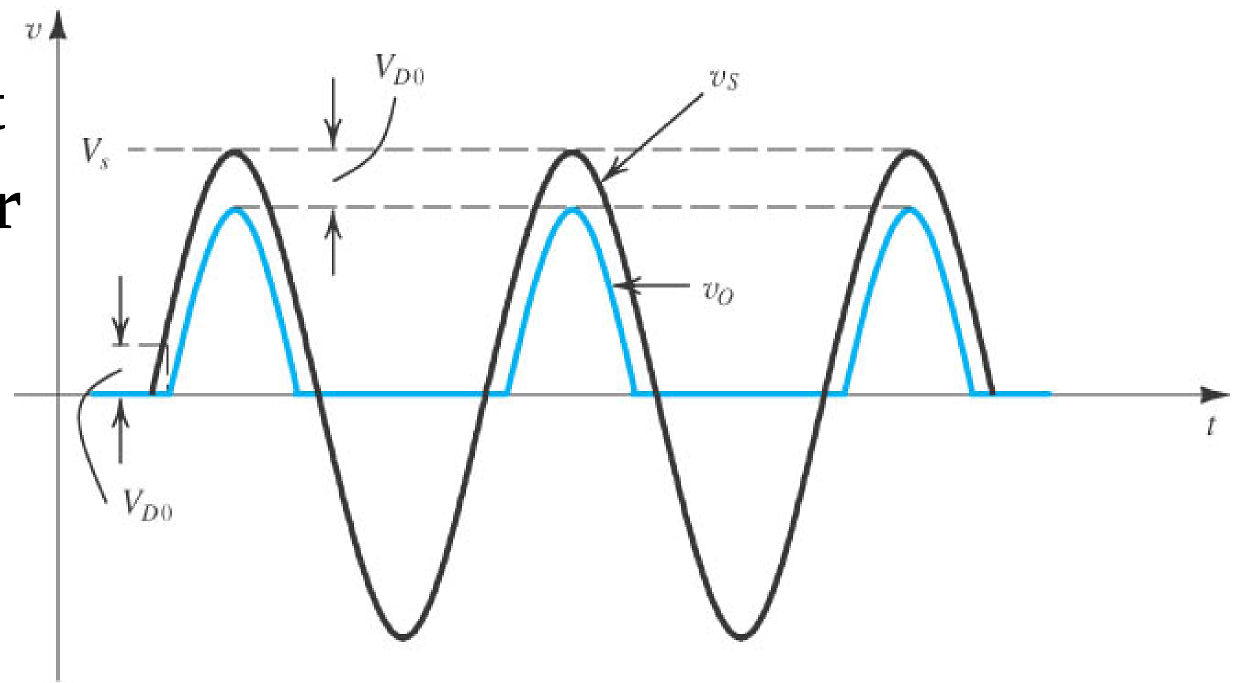


(c)

Half-Wave Rectifier

For $v_S(t) = V_S \sin \omega t$, diode starts to conduct when $V_S \sin \omega t = V_{D0}$ or in terms of conduction angle,

$$\omega t = \sin^{-1} \frac{V_{D0}}{V_S}$$



(d)

Half-Wave Rectifier

Diode stops conduction when $\omega t = \pi - \sin^{-1}\dfrac{V_{D0}}{V_S}$

So for the first period, output voltage $v_O = V_S \sin\omega t - V_{D0}$

for $\left\{\sin^{-1}\dfrac{V_{D0}}{V_S} \le \omega t \le \pi - \sin^{-1}\dfrac{V_{D0}}{V_S}\right\}$

and $v_O = 0$ **, for** $\left\{0 \le \omega t \le \sin^{-1}\dfrac{V_{D0}}{V_S} \ and \ \pi - \sin^{-1}\dfrac{V_{D0}}{V_S} \le \omega t \le 2\pi\right\}$

If $V_S >> V_{D0}$ **, then** $\sin^{-1}\dfrac{V_{D0}}{V_S} \to 0$**, so we have**

$$v_O = (V_S - V_{D0})\sin\omega t \quad \textbf{for} \quad 0 \le \omega t \le \pi$$

$$v_O = 0 \quad \textbf{for} \quad \pi \le \omega t \le 2\pi$$

Half-Wave Rectifier

To find the average load voltage, we have

$$
\begin{aligned}
v_{O(av)} &= \frac{1}{2\pi}\int_0^{2\pi} v_O(\omega t)\,d\omega t \\
&= \frac{1}{2\pi}\int_0^{\pi} \left(V_S - V_{D0}\right)\sin\omega t\,d\omega t \\
&= \frac{V_S - V_{D0}}{2\pi}\int_0^{\pi} \sin\omega t\,d\omega t \qquad \left(= \left[-\cos\omega t\right]_0^{\pi} = 2\right) \\
&= \frac{V_S - V_{D0}}{\pi} \approx \frac{V_S}{\pi}
\end{aligned}
$$

Half-Wave Rectifier

To determine the rms value of v_O,

$$v_{O(rms)} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} v_O^2(\omega t)d\omega t} = \frac{V_S - V_{D0}}{2} \approx \frac{V_S}{2}$$

Ripple factor γ is a measure of the ac content of a waveform, it is defined as:

$$\gamma = \frac{rms\,value\ of\ \ ac\ component}{dc\ (average)\ component} = \frac{v_{O(ac,rms)}}{v_{O(av)}}$$

Half-Wave Rectifier

It would be ideal if $\gamma = 0$, i.e. no ac component.

To find $v_{o(ac,rms)}$, note that rms value measures the power dissipation or heating effect of a waveform on a load.

Let R be the load resistor. Then $P_R = \dfrac{v_{o(rms)}^2}{R}$

This has to be the same as the combined heating effects of the ac and dc (av) components:

$$P_R = \frac{v_{o(rms)}^2}{R} = \left(\frac{v_{o(ac,rms)}^2}{R} + \frac{v_{o(av)}^2}{R} \right)$$

Half-Wave Rectifier

This gives, $v_{O(ac,rms)} = \sqrt{v_{O(rms)}^2 - v_{O(av)}^2}$**, and**

$$\gamma = \frac{\sqrt{v_{o(rms)}^2 - v_{o(av)}^2}}{v_{o(av)}} = \sqrt{\frac{(V_S/2)^2}{(V_S/\pi)^2} - 1} = \sqrt{\frac{\pi^2}{4} - 1} = 1.21$$

Half-Wave Rectifier

Peak inverse voltage (PIV) rating of a diode determines its maximum permissible reverse biased voltage without breakdown.

In the Half-Wave Rectifier circuit, when v_S is negative, the diode is reverse biased and v_O=0,

The maximum reverse biased voltage experienced by the diode is V_S and we have to choose a diode with a minimum PIV = V_S.

Half-Wave Rectifier

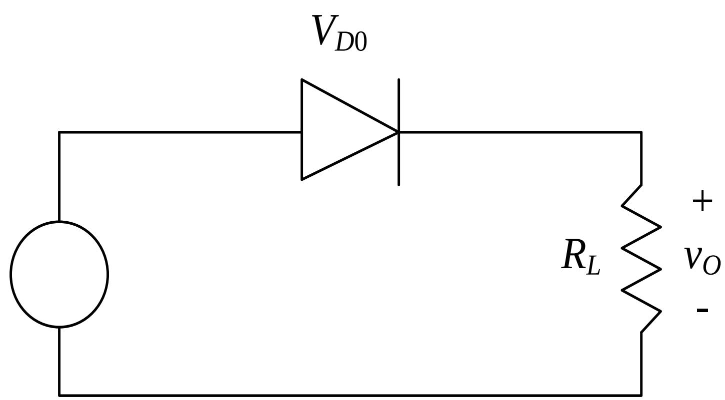
Example 1: A half-wave rectifier using diode for which V_{D0} = 0.7V, is supplied by an 8V_{rms} sine wave at 50 Hz.

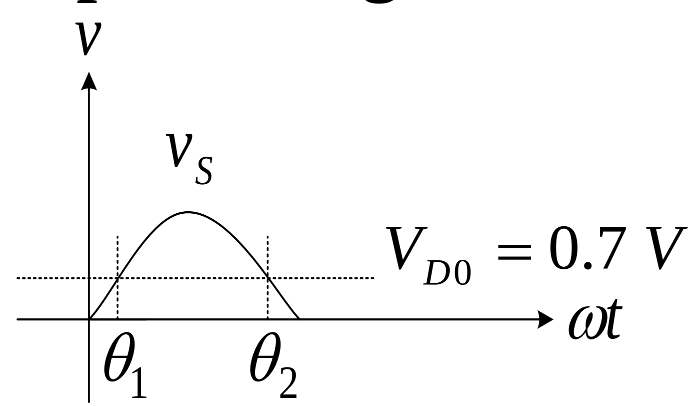
(a) What is the peak value of the output voltage?

(b) For what fraction of a cycle does the diode conduct?

(c) What is the average value of the output voltage?

$$v_S = 8\sqrt{2}\sin \omega t$$





Half-Wave Rectifier

(a) Peak output = $V_S - V_{D0} = 8\sqrt{2} - 0.7 = 10.6\ V$

Diode starts to conduct when voltage across it is equal to 0.7 V, so $V_S \sin \omega t = V_{D0}$ **or** $\theta_1 = \omega t_1 = \sin^{-1}\dfrac{V_{D0}}{V_S} = \sin^{-1}\dfrac{0.7}{8\sqrt{2}} = 3.55°$

Diode stops conducting when $\theta_2 = \pi - \sin^{-1}\dfrac{V_{D0}}{V_S} = 176.45°$

(b) So diode conducts for $\dfrac{\theta_2 - \theta_1}{360°} = \dfrac{176.45° - 3.55°}{360°} = 48\%$

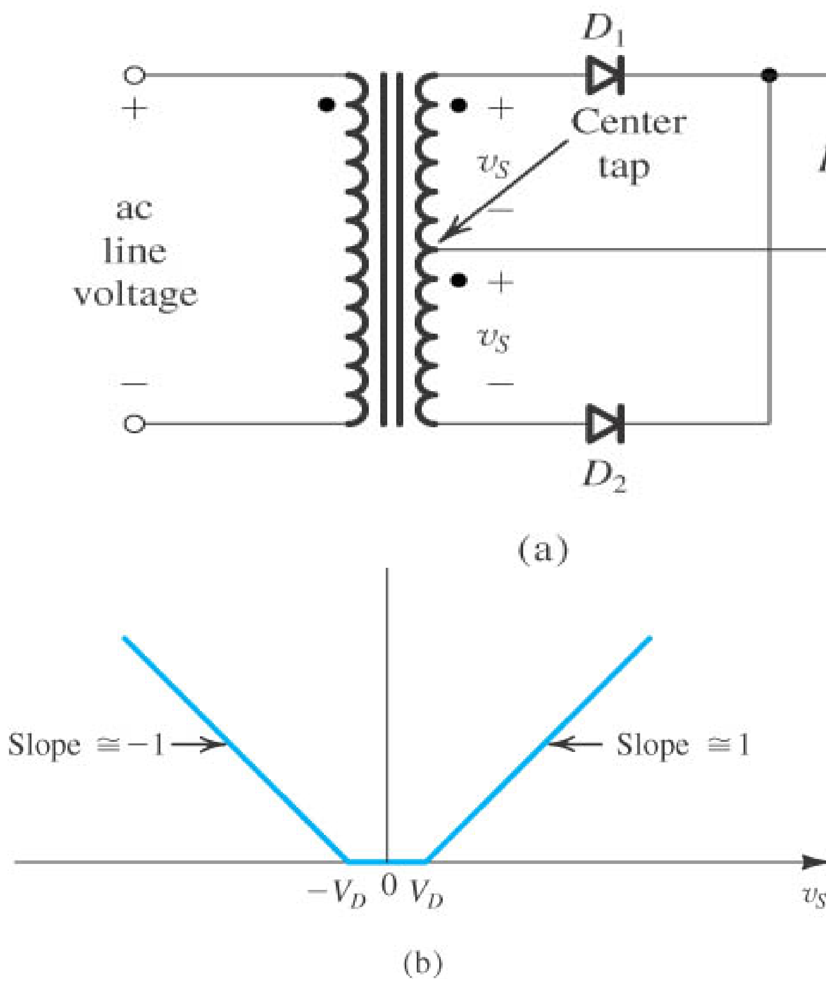
(c) Average output: $v_{O(av)} = \dfrac{V_S - V_{D0}}{\pi} = 3.37\ \text{V}$

Full-Wave Rectifier

For v_S sufficiently positive, D_1 conducts and D_2 is reverse biased.

For v_S sufficiently negative, D_2 conducts and D_1 is reverse biased.

$$PIV = 2V_S - V_{D0} \approx 2V_S$$

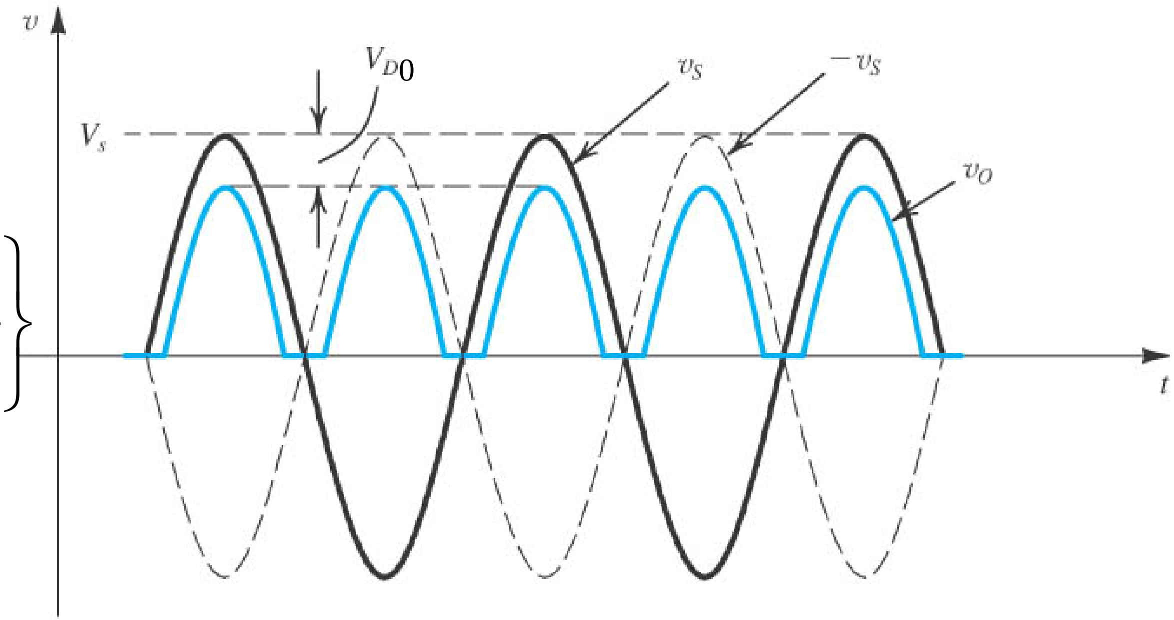


Full-Wave Rectifier

$$v_o = V_S \sin \omega t - V_{D0}$$

when

$$\left\{ \sin^{-1}\frac{V_{D0}}{V_S} \le \omega t \le \pi - \sin^{-1}\frac{V_{D0}}{V_S} \right\}$$



(c)

$$v_o = 0$$

for $\left\{ 0 \le \omega t \le \sin^{-1}\frac{V_{D0}}{V_S} \; and \; \pi - \sin^{-1}\frac{V_{D0}}{V_S} \le \omega t \le \pi \right\}$

Full-Wave Rectifier

If $V_s >> V_{D0}$, then $v_o = (V_S - V_{D0})\sin \omega t$ **for** $0 \le \omega t \le \pi$

The average component can be similarly found as

$$v_{O(av)} = \frac{1}{2\pi}\int_0^{2\pi} v_o(\omega t)d\omega t \approx \frac{2V_S}{\pi}$$

and the rms value as

$$v_{O(rms)} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} v_o^2(\omega t)d\omega t} = \frac{V_S - V_D}{\sqrt{2}} \approx \frac{V_S}{\sqrt{2}}$$

Full-Wave Rectifier

Hence the ripple factor can be calculated:

$$\gamma = \frac{v_{o(ac,rms)}}{v_{o(av)}} = \frac{\sqrt{v_{o(rms)}^2 - v_{o(av)}^2}}{v_{o(av)}} = \sqrt{\frac{\pi^2}{8} - 1} = 0.483$$

As expected, the full-wave rectifier has smaller ripple factor than that of half-wave rectifier.

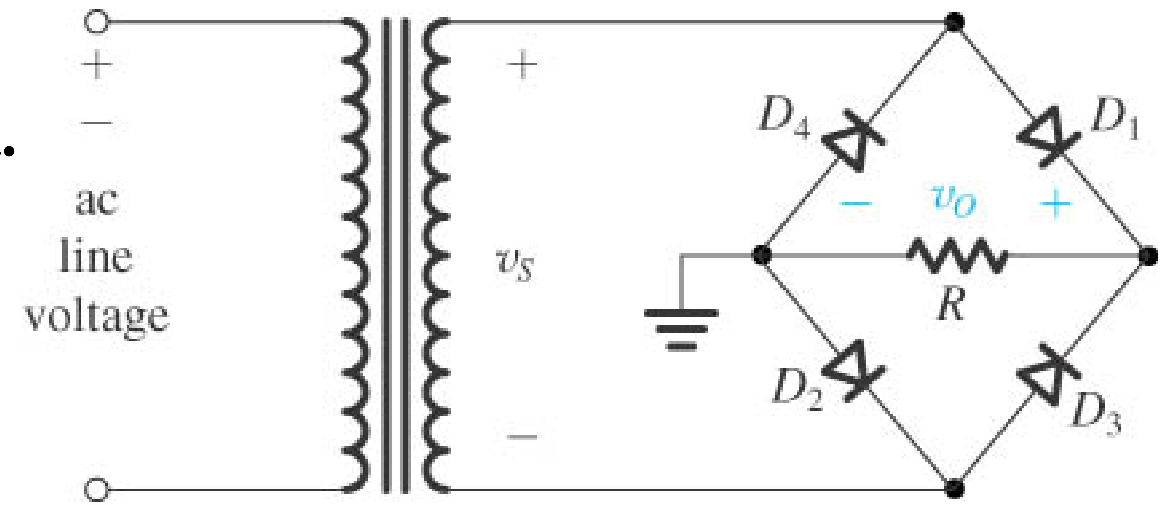
Full-Wave Bridge Rectifier

No need for center-tapped transformer.

$V_S \sin \omega t$ **positive,**
D_1 and D_2 conduct.

$V_S \sin \omega t$ **negative,**
D_3 and D_4 conduct.

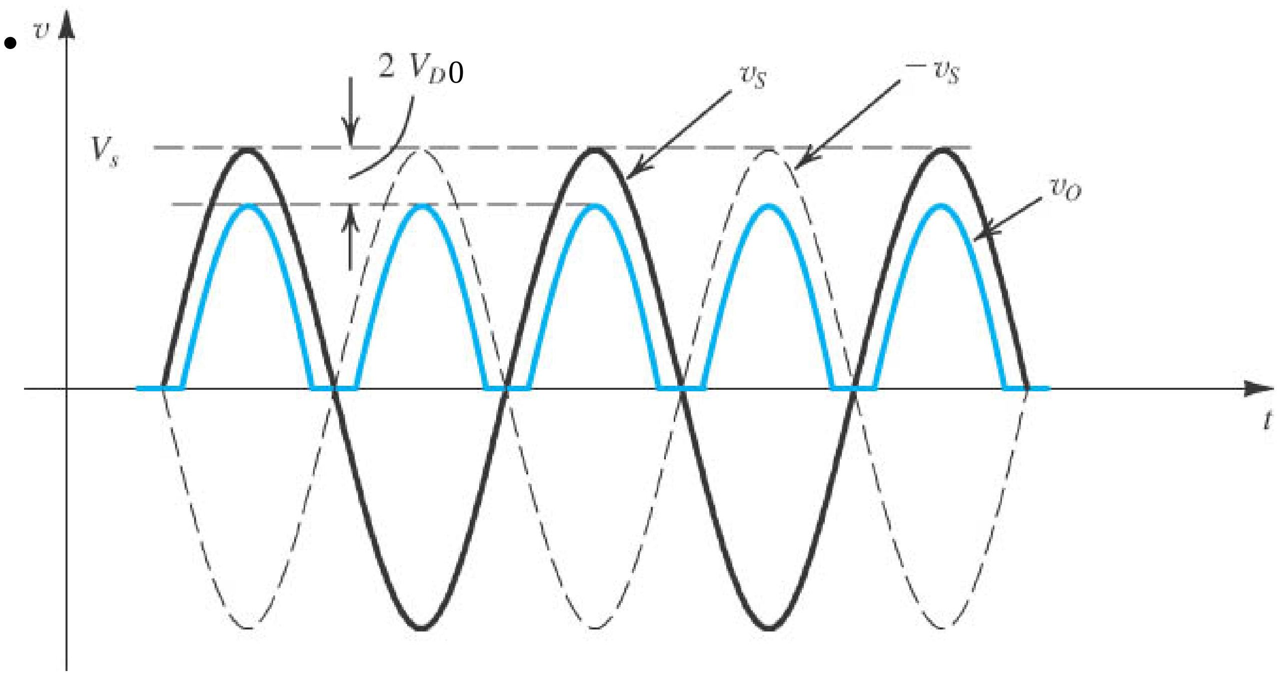
$$PIV = V_S - V_{D0}$$



(a)

Full-Wave Bridge Rectifier

Equations for full-wave rectifier are valid in full-wave bridge rectifier, except that the total diode voltage drop is 2V_{D0} instead of V_{D0}.



(b)

Full-Wave Bridge Rectifier

Example 2: A transformer secondary winding whose output is 12V$_{rms}$ sinusoid at 50 Hz is used to drive a bridge rectifier, whose diodes' conduction can be modeled by 0.7V drops. The load is a 1kΩ resistor.

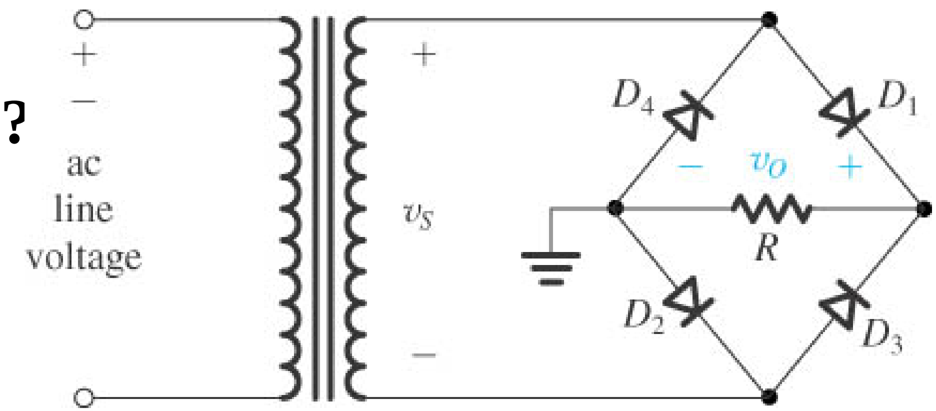
(a) Sketch the load voltage waveform.

(b) What is the peak value?

(c) Over what time interval is it zero?

(d) What is the average value?

(e) What is the PIV for each diode?



(a)

Full-Wave Bridge Rectifier

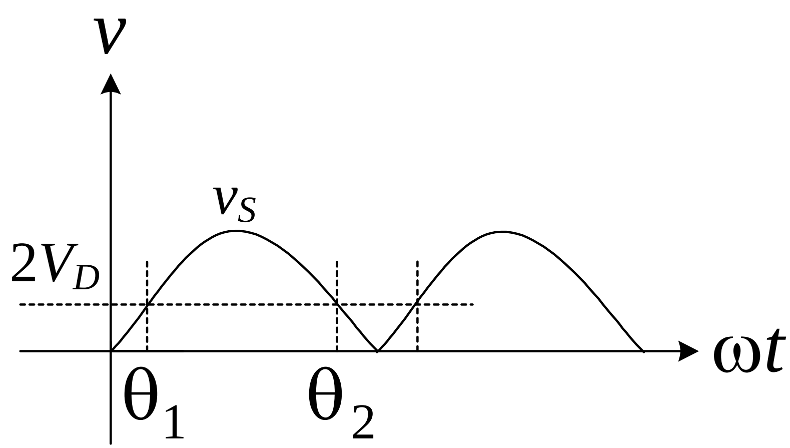
(a) The load voltage waveform as shown on page 22.

(b) The transformer peak voltage, $V_S = 12\sqrt{2} = 16.97\ V$

Load peak voltage, $V_O = 16.97 - 2 \times 0.7 = 15.57\ V$

(c) From the figure below, we have $V_S \sin\theta_1 = 2V_{D0}$

$$\theta_1 = \sin^{-1}\frac{2V_{D0}}{V_S} = \sin^{-1}\frac{1.4}{16.97} = 4.73°$$



Within one period, there are four such intervals, so the time interval in one period:

$$\frac{4 \times 4.73°}{360°} \times \frac{1}{50} = 1.05\ ms$$

Full-Wave Bridge Rectifier

(d) The average output

$$v_{o(av)} = \frac{2(V_S - 2V_{D0})}{\pi} = 9.91\,V$$

(e) PIV for each diode:

$$V_{PIV} = V_S - V_{D0} = 16.97 - 0.7 = 16.27\ V$$

Filter

For 50 Hz ac source, rectified output comprises: dc component, ac fundamental component of 50 Hz, and ac harmonic components that are integer multiples of 50Hz.

For smooth output voltage, the ac components have to be removed or reduced. A low pass filter needs to be used to filter those ac components.

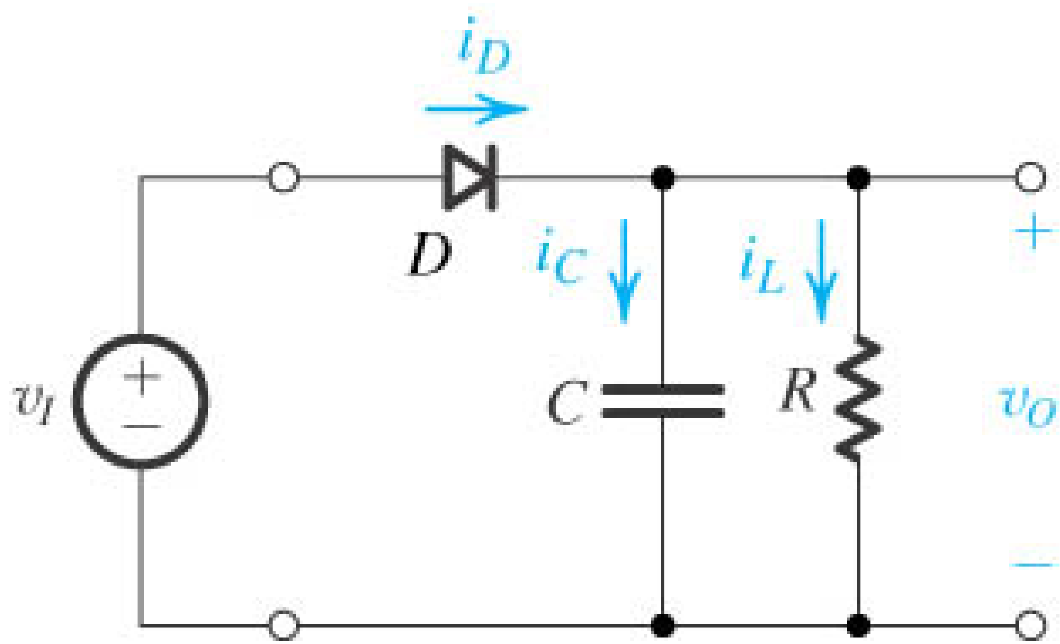
The quality of the filtered voltage is expressed by the ripple factor. A good filter should greatly reduce the ripple factor.

Filter

With a load *R* connected across the capacitor, the capacitor discharges when the diode is off.

Capacitor will be charged up to V_P when the diode conducts for $v_O < v_I$.

$RC >> T$, the input period to reduce the output voltage drop.



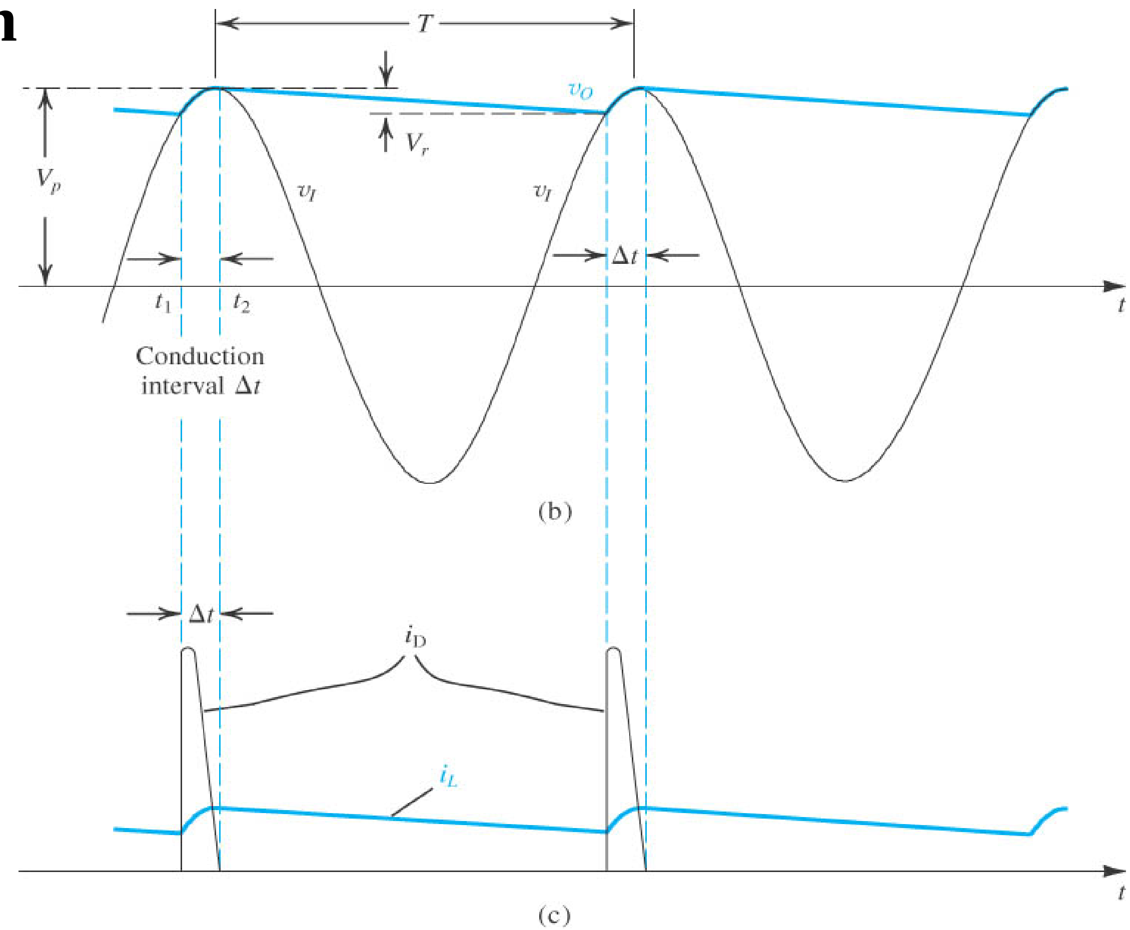
Filter

Since *RC* >>*T*, it can be shown that the peak-to-peak ripple voltage:

$$V_r \approx \frac{V_P}{fRC}$$

where *f* = 1/*T* is the input frequency. The output dc (average) voltage:

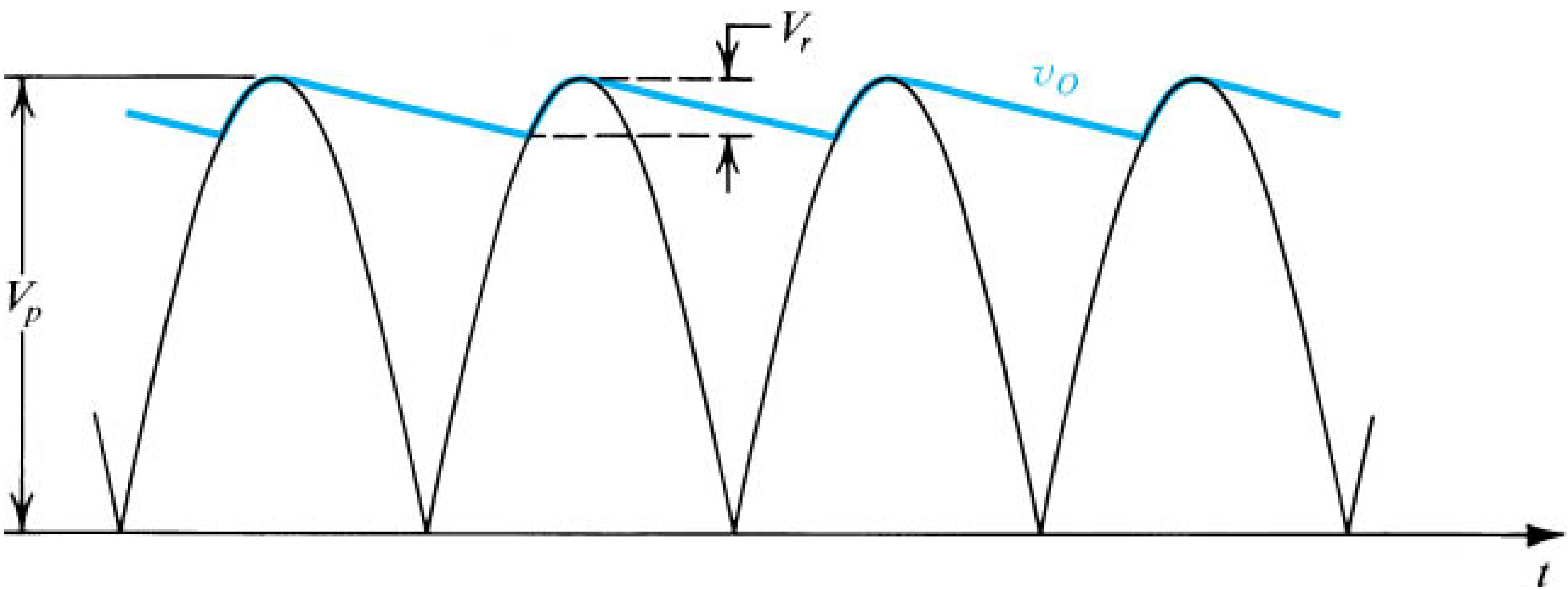
$$V_O = V_P - \frac{1}{2} V_r$$



Filter

For Full-Wave Rectifier, with *RC* >> *T*, the peak-to-peak ripple voltage is:

$$V_r \approx \frac{V_P}{2fRC}$$



Filter

Example 3: A full-wave bridge rectifier with a capacitor filter is driven by a 50Hz 12V$_{rms}$ sinusoid to drive a 100Ω load. The ripple voltage should not exceed 0.4V peak-to-peak. Assume that diodes' conduction can be modeled by 0.7V drops, determine the required capacitance of the filter capacitor and the dc output.

(a) The filter capacitor peak input voltage is:

$$V_P = 12\times\sqrt{2} - 2V_{D0} = 12\times\sqrt{2} - 2\times 0.7 = 15.57\ V \quad \textbf{and} \quad R_L = 100\ \Omega$$

Hence, $$C = \frac{V_P}{2fRV_r} = \frac{15.57}{2\times 50\times 100\times 0.4} = 3892.5\mu\text{F}$$

(b)The dc output voltage is: $$V_O = V_P - \frac{1}{2}V_r = 15.57 - \frac{1}{2}\times 0.4 = 15.37\text{V}$$

Voltage Regulator

An ideal voltage regulator maintains a constant dc output voltage, irrespective of external factors.

Output voltage from a practical voltage regulator is affected by a number of factors, such as:

(a) Load variations

(b) Line variations

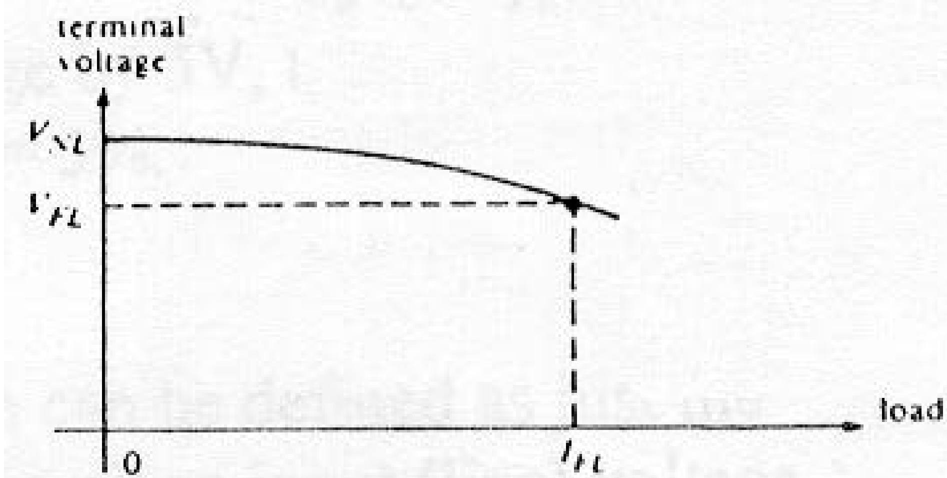
(c) Ambient temperature variations

Voltage Regulator

Load regulation is the change in output voltage (or current for current source) for any given load change within the specified limits, with the other factors such as input line voltage and ambient temperature held constant. The specified limit is usually the no-load voltage and the full-load voltage.

Load regulation is defined as:

$$VR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

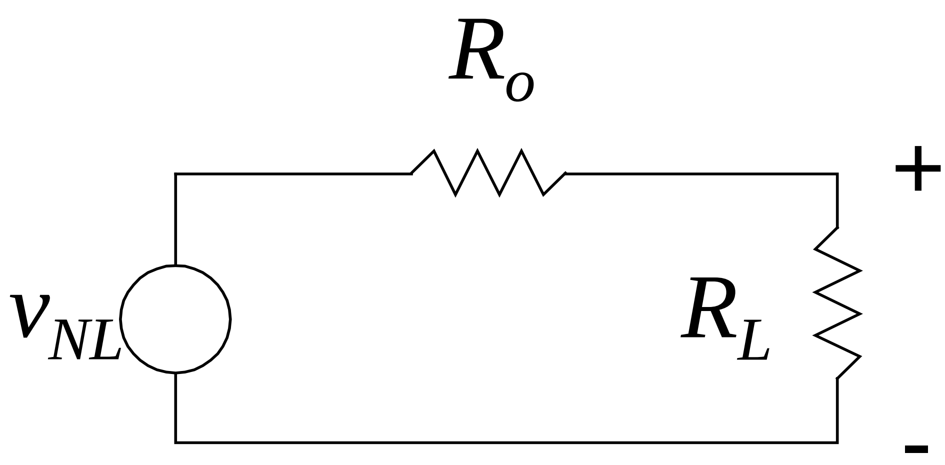


No-load and full-load conditions in a power supply

Voltage Regulator

Model the power supply with Thevenin equivalent circuit, with an output resistance R_o. Note that the slope of load voltage versus load current gives the output resistance:

$$R_0 = \frac{\Delta V_L}{\Delta I_L}$$



$$\left(\frac{R_L}{R_L + R_o}\right) V_{NL}$$

Voltage Regulator

In general, the terminal voltage changes nonlinearly with load current (e.g. see earlier V_L vs I_L plot). The result is that output resistance R_o depends on the actual load current.

Since we are usually concerned with the performance of a power supply at its rated or full-load output, R_o is usually specified as full-load. Let the full-load resistance be

$$R_{FL} = \frac{V_{FL}}{I_{FL}}$$

By voltage-divider,

$$V_{FL} = \left(\frac{R_{FL}}{R_{FL} + R_o} \right) V_{NL}$$

Voltage Regulator

Load regulation is calculated by:

$$VR = \frac{V_{NL} - \left(\dfrac{R_{FL}}{R_{FL} + R_o}\right) \cdot V_{NL}}{\left(\dfrac{R_{FL}}{R_{FL} + R_o}\right) \cdot V_{NL}} = \frac{R_0}{R_{FL}} = R_0 \left(\frac{I_{FL}}{V_{FL}}\right)$$

Comments: $VR \propto R_0$. **If** $R_0 = 0$, **then** $VR = 0\ \%$.

Low R_o **is essential for low load regulation.**

Voltage Regulator

Line regulation is the percentage change in the output voltage that occurs per one-volt change in input (line) voltage.

Line regulation is defined as:

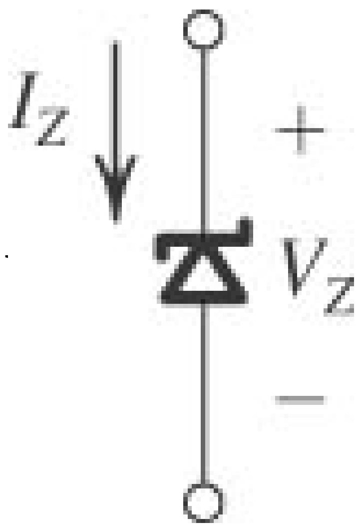
$$\frac{\Delta V_o / V_o}{\Delta V_{in}} \times 100\% \qquad \textbf{(unit = \% / V)}$$

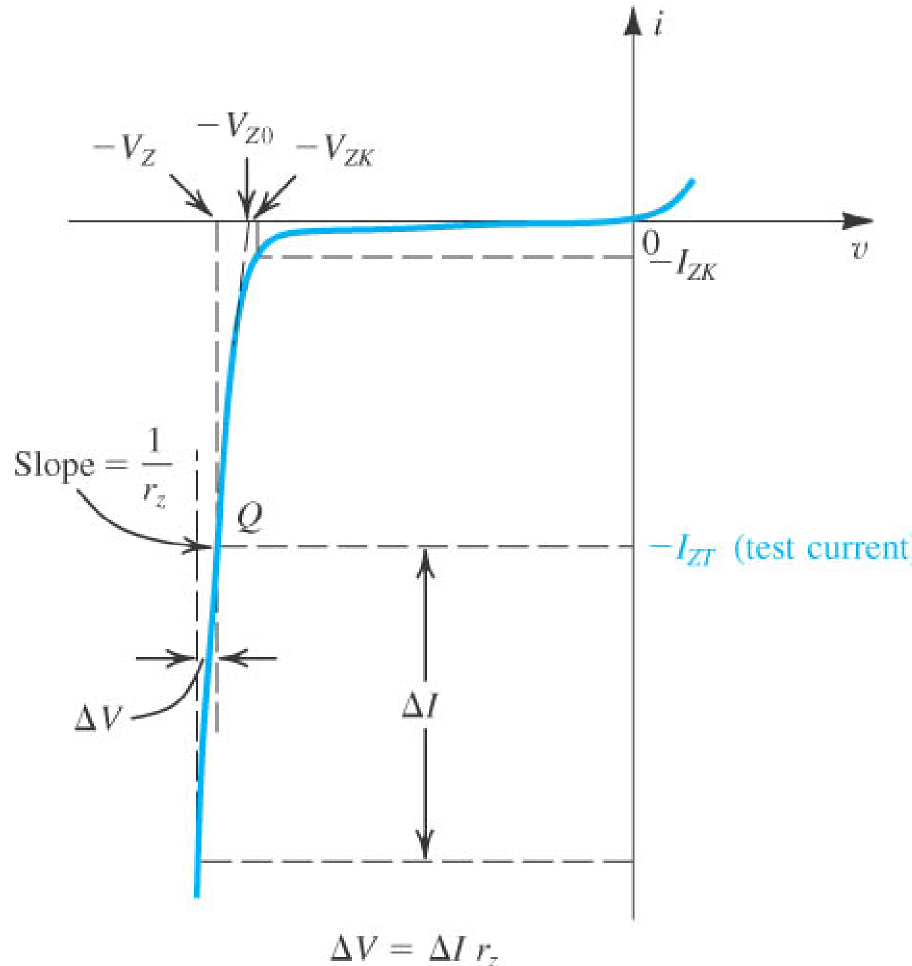
If the input to power supply having a 1%/V line regulation is to change by 5 V, then the output will change by (5 V)(1%/V) = 5 %.

Voltage Regulator

Zener diodes are also called breakdown diodes and widely used in realizing voltage regulator.

Zener diodes are to be used in the reverse region.





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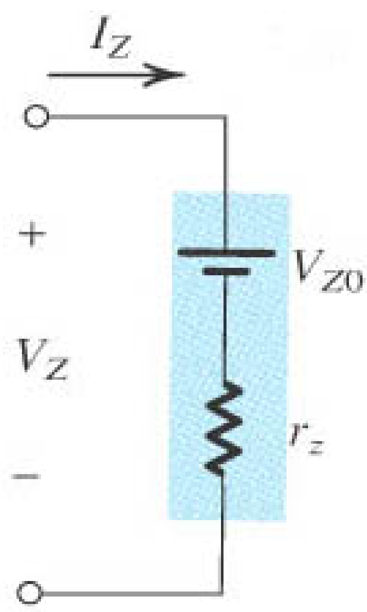
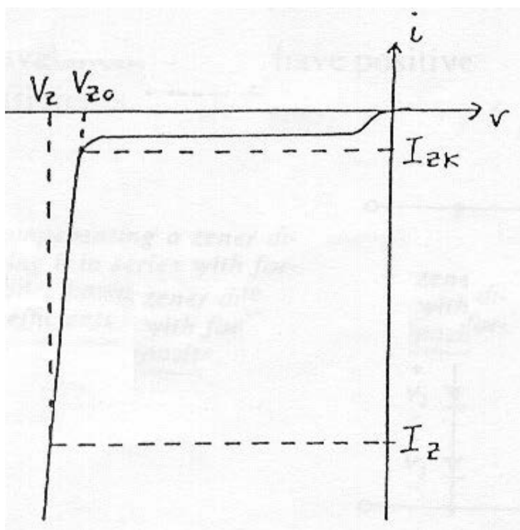
Voltage Regulator

The breakdown characteristics of an ideal Zener diode is a perfectly vertical line, signifying zero change in voltage, for any change in current.





$$V_Z = V_{ZO} + r_Z (I_Z - I_{ZK})$$

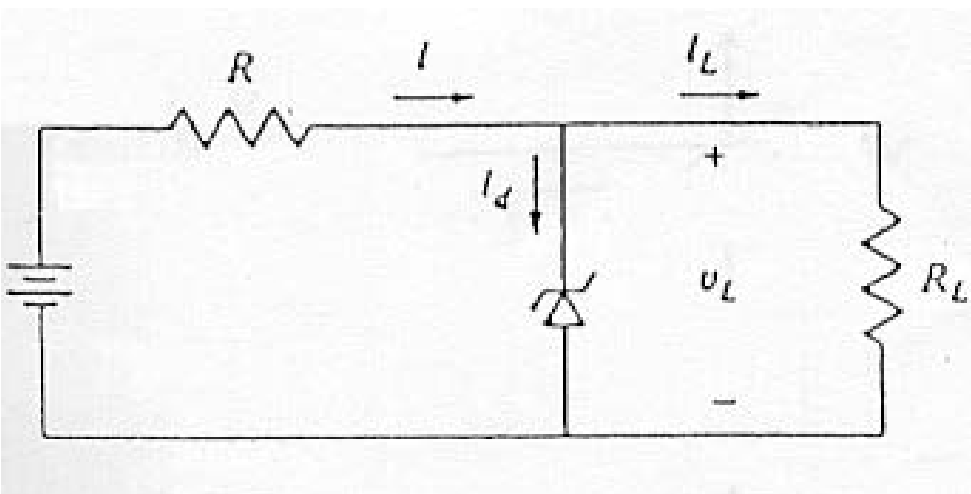
$$for \;\; I_Z > I_{ZK}$$

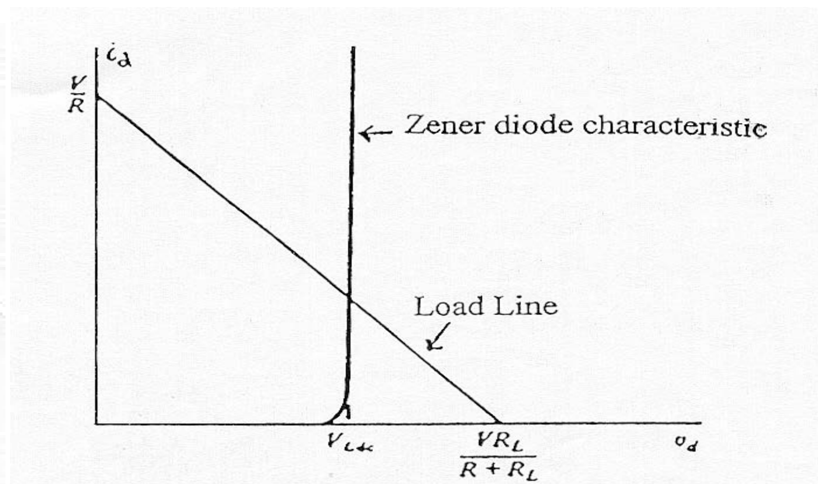
$$and \;\; V_Z > V_{ZO}$$

where r_Z is the incremental or dynamic resistance. I_{ZK} is the knee current, min I required to drive the Zener diode to obtain reverse breakdown. The corresponding voltage is called knee voltage.

Voltage Regulator

The Zener diode is connected in parallel with load. As long as unregulated power supply is large enough to cause reverse breakdown, V_L is almost constant. Suppose the unregulated voltage changes, load line shifts parallel to itself. Suppose R_L changes, slope of load line changes. However, in both cases, V_L changes little. Any changes in V_L depend on the characteristics of the Zener diode.





The voltage-current characteristics for a Zener diode. Note that the breakdown region (reverse bias) is plotted.

Voltage Regulator

Example 5: A 6.8 V Zener diode specified at 5mA with r_Z = 20Ω and I_{ZK} = 0.2mA, is operated in a regulator circuit using a 200Ω resistor. For no-load, what is the lowest supply voltage for which the Zener remains in breakdown operation? For a supply voltage of 9 V, what is the maximum load current for which the Zener remains in breakdown operation?

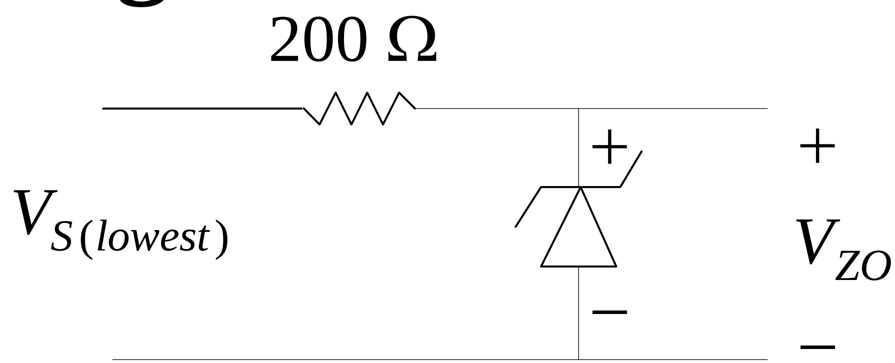
Since $V_Z = 6.8\ V$, $I_Z = 5\ mA$, $r_Z = 20\Omega$, $I_{ZK} = 0.2\ mA$,

$$V_Z = V_{ZO} + r_Z(I_Z - I_{ZK})$$

$$V_{ZO} = V_Z - r_Z(I_Z - I_{ZK})$$

$$= 6.8 - (5 - 0.2) \times (20) \times 10^{-3} = 6.7\ V$$

Voltage Regulator

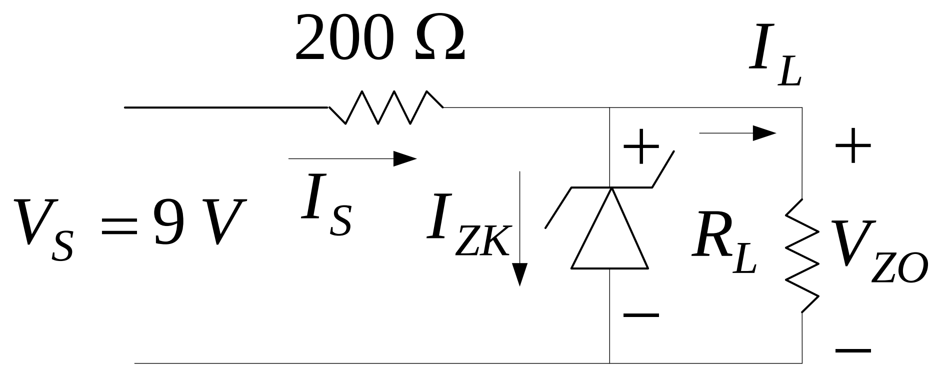


For no-load breakdown,

$$V_{S(lowest)} = V_{ZO} + I_{zk} \times 200 = 6.74\ V$$

Supply voltage lower than this,

no breakdown. $I_S = I_{ZK} + I_L$



From the diagram,

$$I_S = \frac{9 - 6.7}{200} = 11.5\ mA$$

So, the maximum load current for which the Zener remains in breakdown: $I_L = I_S - I_{ZK} = 11.5 - 0.2 = 11.3\ mA$

Voltage Regulator

Zener diodes are available with breakdown voltage ranging from 2.4 V to 200 V. Temperature coefficient of a Zener diode:

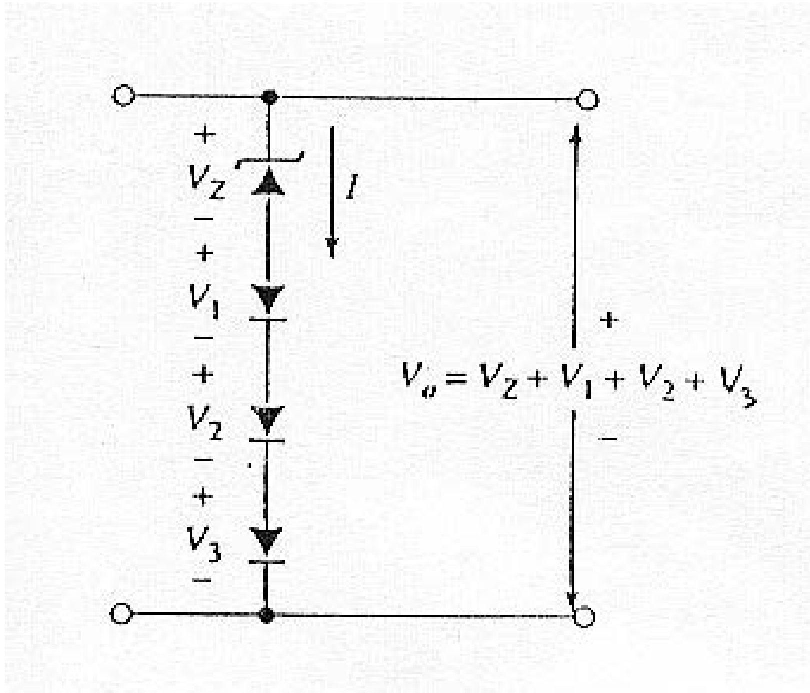
$$T.C. = \frac{\Delta V_Z}{\Delta T} \quad (mV / °C)$$

Low-voltage Zener diodes (<5 V) break down by *Zener mechanism* have *negative* temperature coefficients. Between 5 V and 8 V, both avalanching and Zener mechanisms contribute to breakdown; the coefficients may be positive or negative, depending on current.

Voltage Regulator

Higher-voltage avalanche Zener diodes have positive temperature coefficients. Temperature-compensated Zener diodes are available, but must be operated at manufacture's specified value.

Temperature compensating a Zener diode by connecting it in series with forward-biased diodes having opposite temperature coefficients.



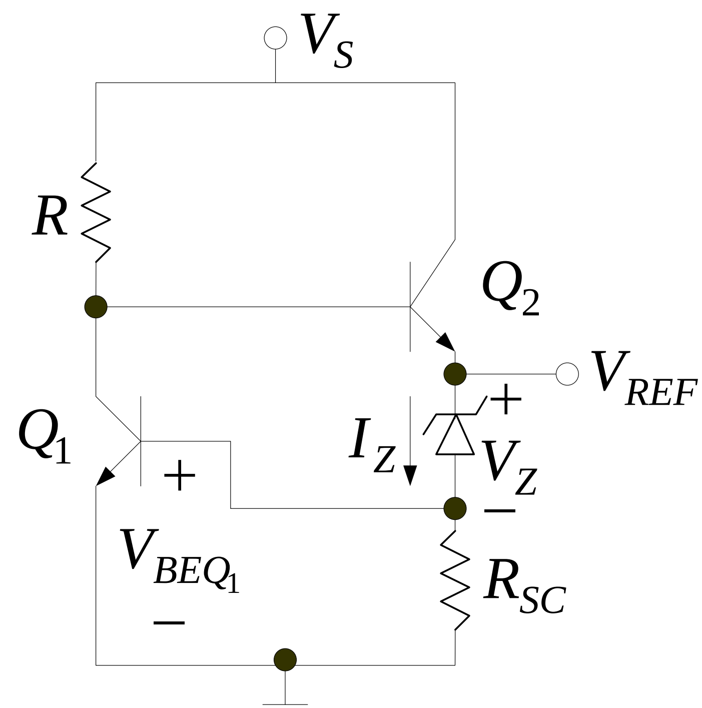
Voltage Regulator

For the simple circuit, Zener current is sensitive to fluctuation in unregulated voltage *Vs*. To improve regulation, it is important to keep Zener current insensitive to unregulated voltage *Vs* changes.

Operation:

$$V_{REF} = V_Z + V_{BEQ_1} = V_{ZO} + I_Z r_Z + V_{BEQ_1}$$

$$= V_{ZO} + V_{BEQ_1}\left(1 + \frac{r_Z}{R_{SC}}\right)$$



So V_{REF} is not sensitive to V_S changes. To further prevent changes in the Zener current, the reference output is usually fed into a very high impedance op-amp.