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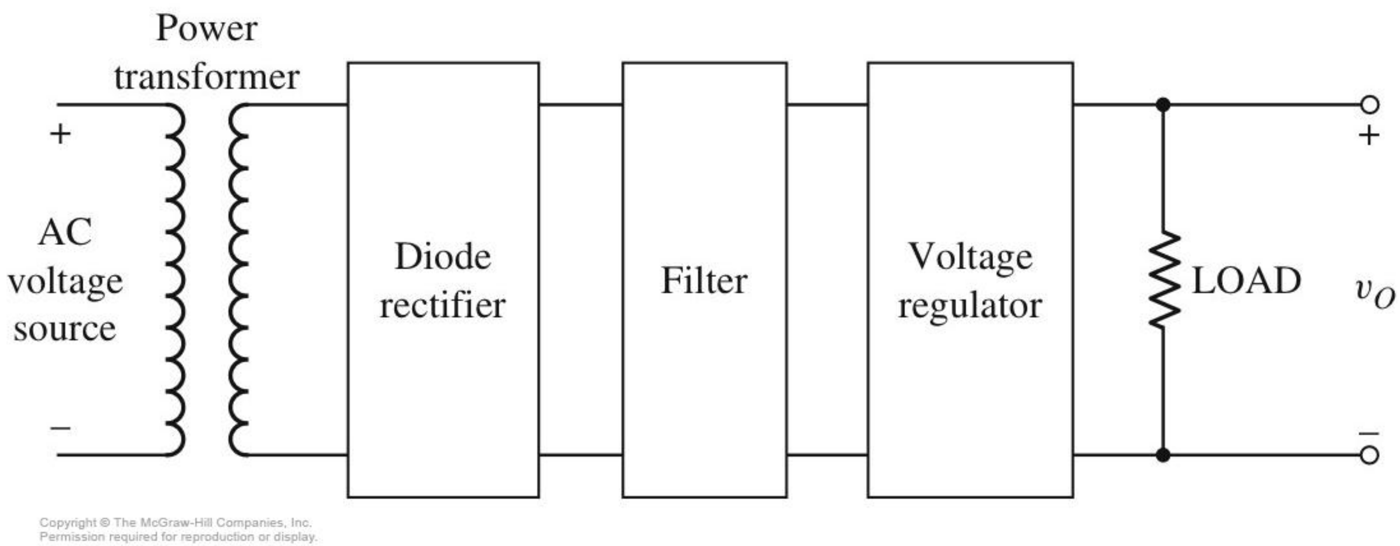
EEE109: Electronic Circuits

Diode Circuits

Contents of Chapter 2

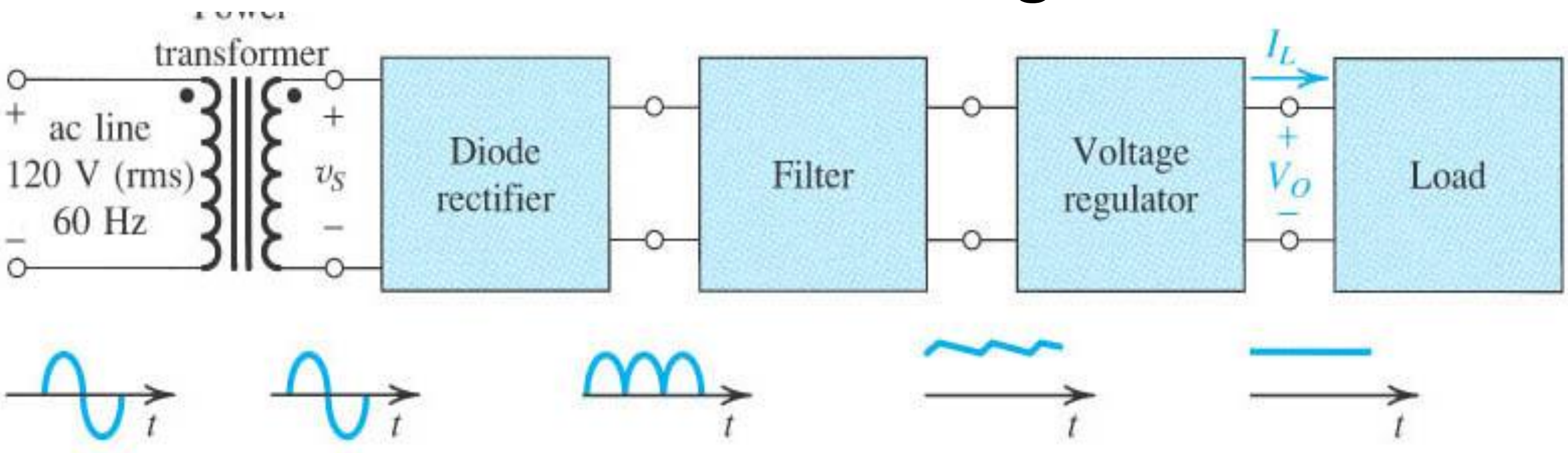
- Determine the operation and characteristics of diode rectifier circuits, which is the first stage of the process of converting an ac signal into a dc signal in the electronic power supply.
- Apply the characteristics of the Zener diode to a Zener diode voltage regulator circuit.
- Apply the nonlinear characteristics of diodes to create waveshaping circuits known as clippers and clampers.
- Examine the techniques used to analyze circuits that contain more than one diode.
- Understand the operation and characteristics of specialized photodiode and light-emitting diode circuits.

Block Diagram for ac to dc Converter



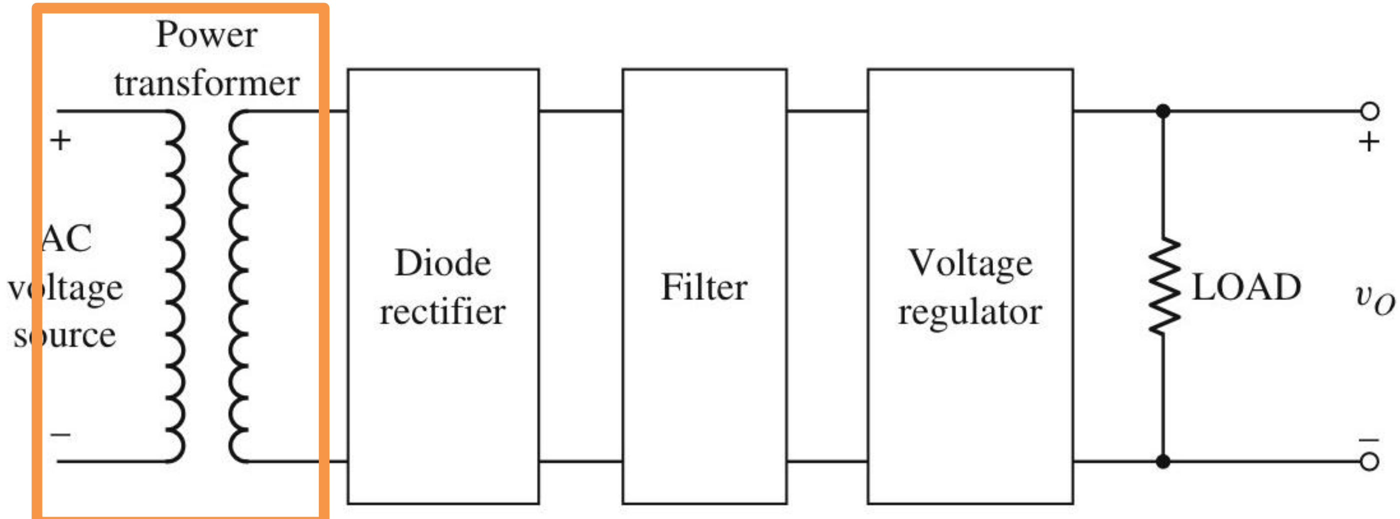
The diode rectifier, filter, and voltage regulator are diode circuits.

Rectifier Circuits Using Diodes



- Basic rectifier converts an ac voltage to a pulsating dc voltage.
- A filter then eliminates ac components of the waveform to produce a nearly constant dc voltage output.
- Rectifier circuits are used in virtually all electronic devices to convert the 120 V-60 Hz ac power line source to the dc voltages required for operation of the electronic device.
- In rectifier circuits, the diode state changes with time and a given piecewise linear model is valid only for a certain time interval.

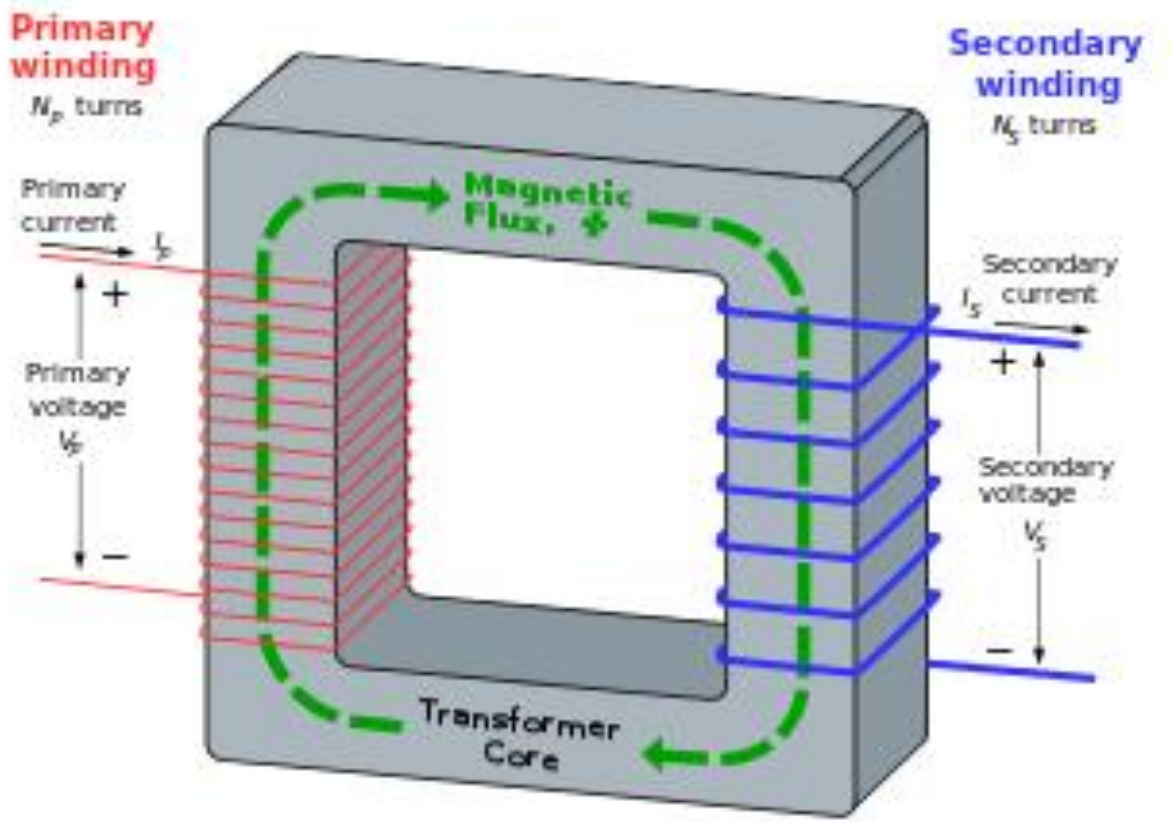
Block Diagram for ac to dc Converter



The diode rectifier, filter, and voltage regulator are diode circuits.

Transformer

- A **transformer** is an electrical device that transfers energy between two or more circuits through electromagnetic induction.



Ideal transformer equations

- By **Faraday's law of induction**

The induced electromotive force in any closed circuit is equal to the negative of the time rate of change of the magnetic flux enclosed by the circuit

$$V_S = -N_S \frac{d\Phi}{dt} \quad (1)$$

$$V_P = -N_P \frac{d\Phi}{dt} \quad (2)$$

- Combining ratio of (1) & (2)

Turns ratio $= \frac{V_P}{V_S} = \frac{-N_P}{-N_S} = a$ (3)

Where for step-down transformers, a > 1; for step-up transformers, a < 1.

- By **law of Conservation of Energy**, apparent, real and reactive power are each conserved in the input and output

$$S = I_P V_P = I_S V_S \quad (4)$$

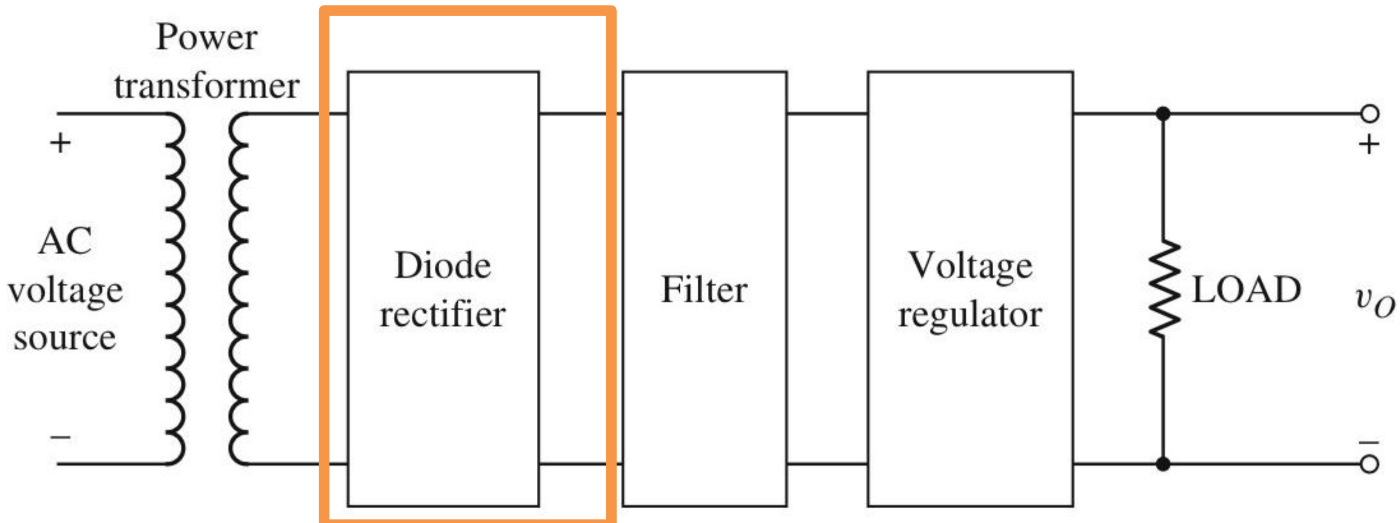
- Combining (3) & (4) with this endnote yields the **ideal transformer identity**:

$$\frac{V_P}{V_S} = \frac{I_S}{I_P} = \frac{N_P}{N_S} = \sqrt{\frac{L_P}{L_S}} = a \quad (5)$$

Problem-Solving Technique: Diode Circuits

1. Determine the input voltage condition such that the diode is conducting (on).
   a. Find the output signal for this condition.
2. Determine the input voltage such that the diode is not conducting (off).
   a. Find the output signal for this condition.

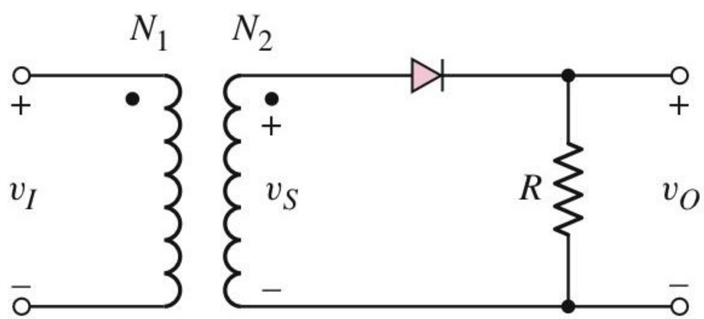
Block Diagram for ac to dc Converter



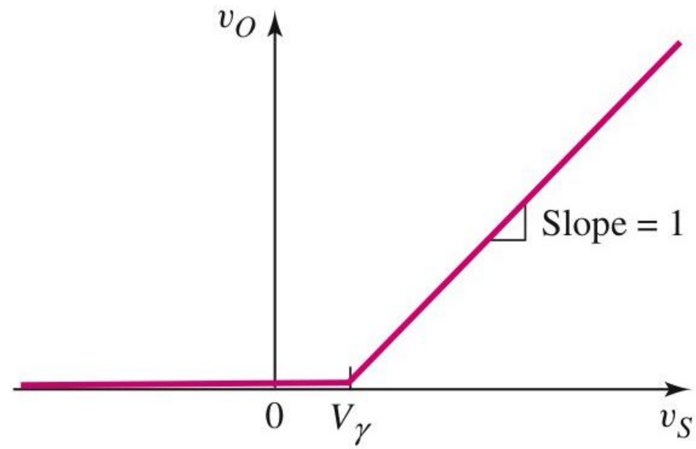
The diode rectifier, filter, and voltage regulator are diode circuits.

Half-wave Rectification

Half-Wave Rectifier



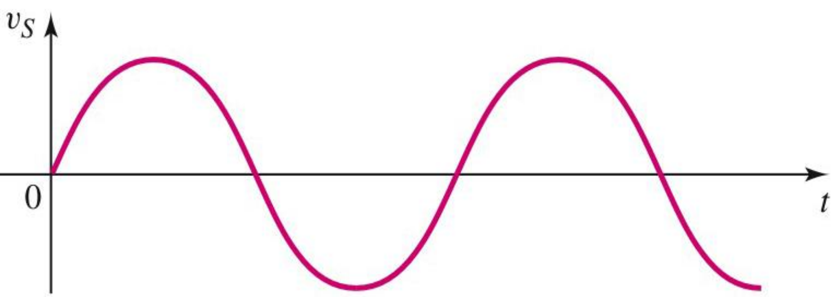
(a)



(b)

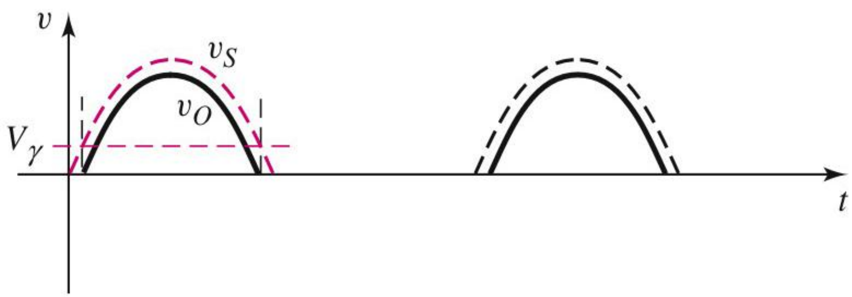
Voltage Transfer Characteristics

Signals of Half Wave Rectifier



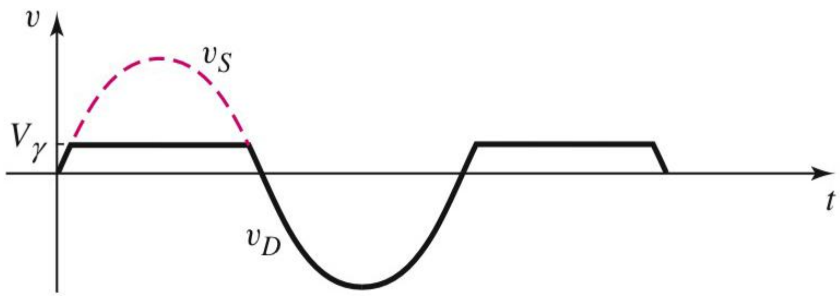
(a)

Input voltage



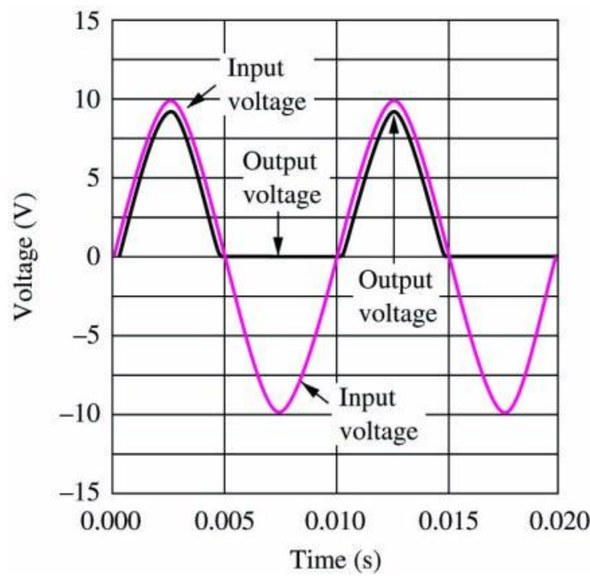
(b)

Output voltage



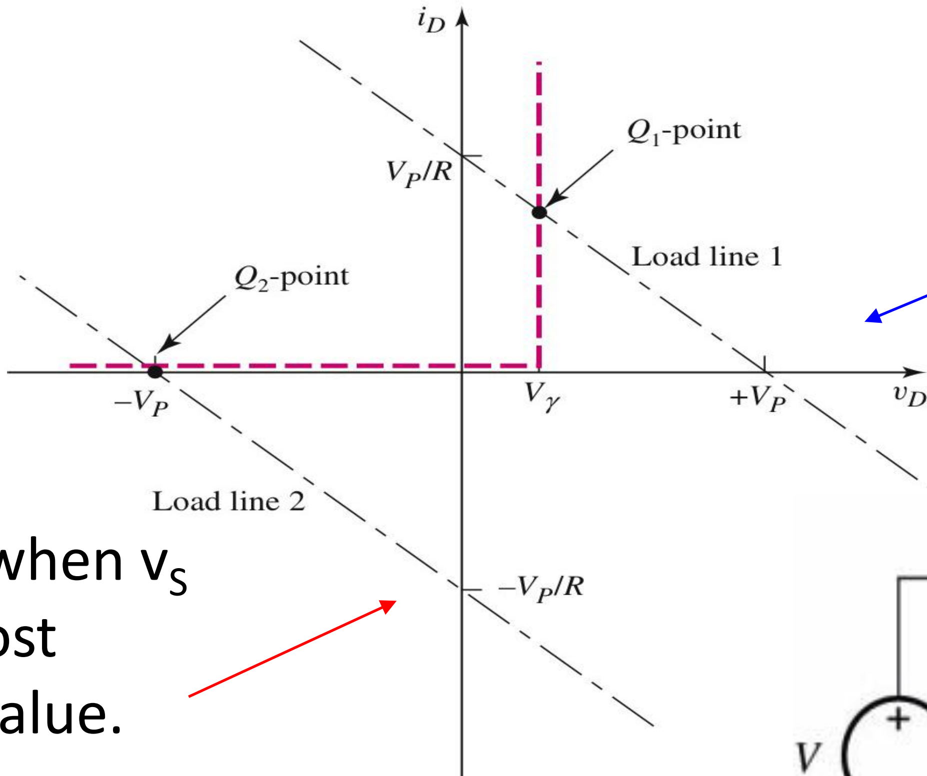
(c)

Diode voltage



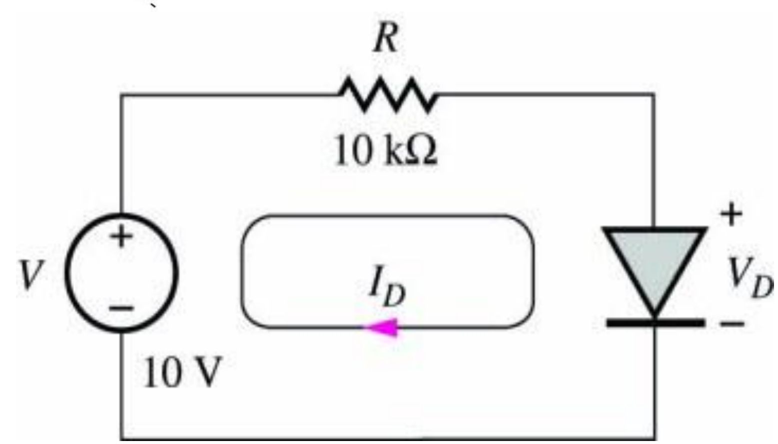
1. Peak current in the **forward direction**;
2. Largest peak inverse voltage (PIV) at **reverse direction**.

Load Line Analysis



Load line when v_S is at its maximum forward voltage.

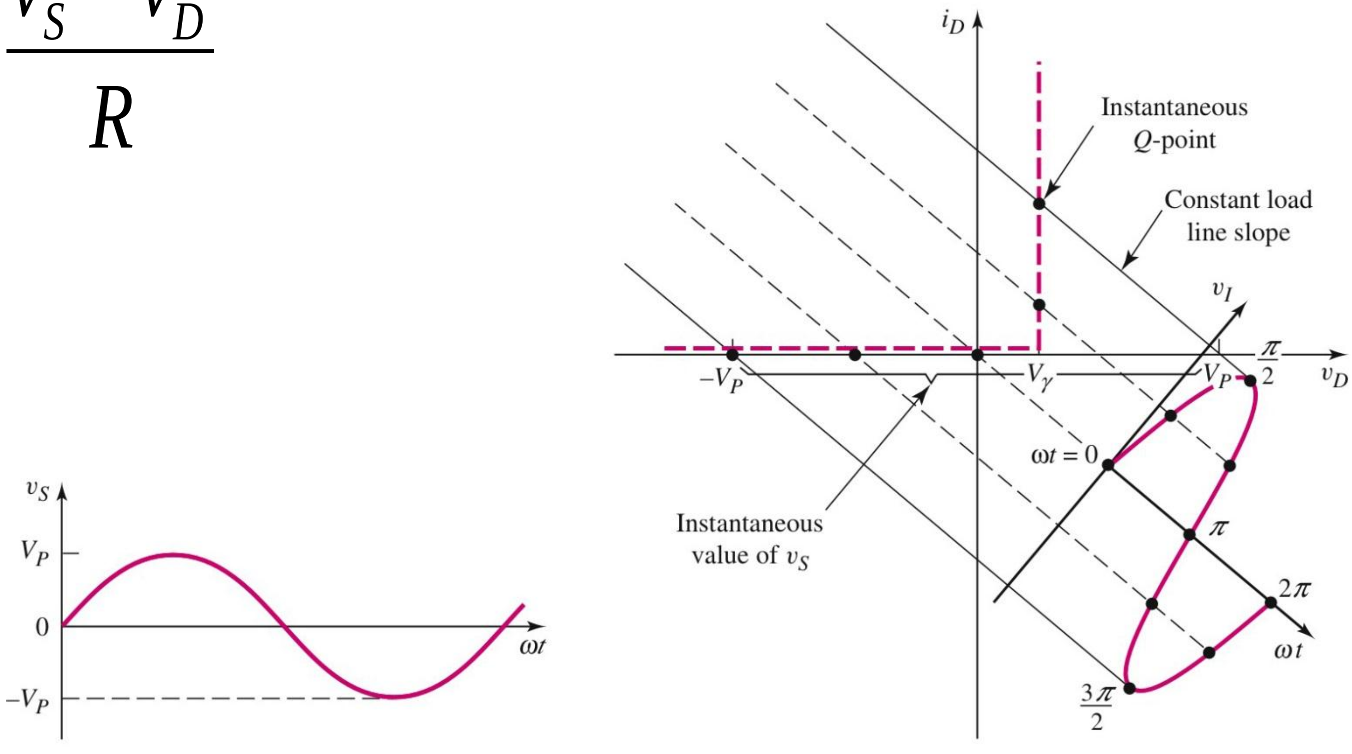
Load line when v_S is at its most **neg**ative value.



$$i_D = \frac{V_P - v_D}{R}$$

Load Line (con't)

$$i_D = \frac{v_S - v_D}{R}$$

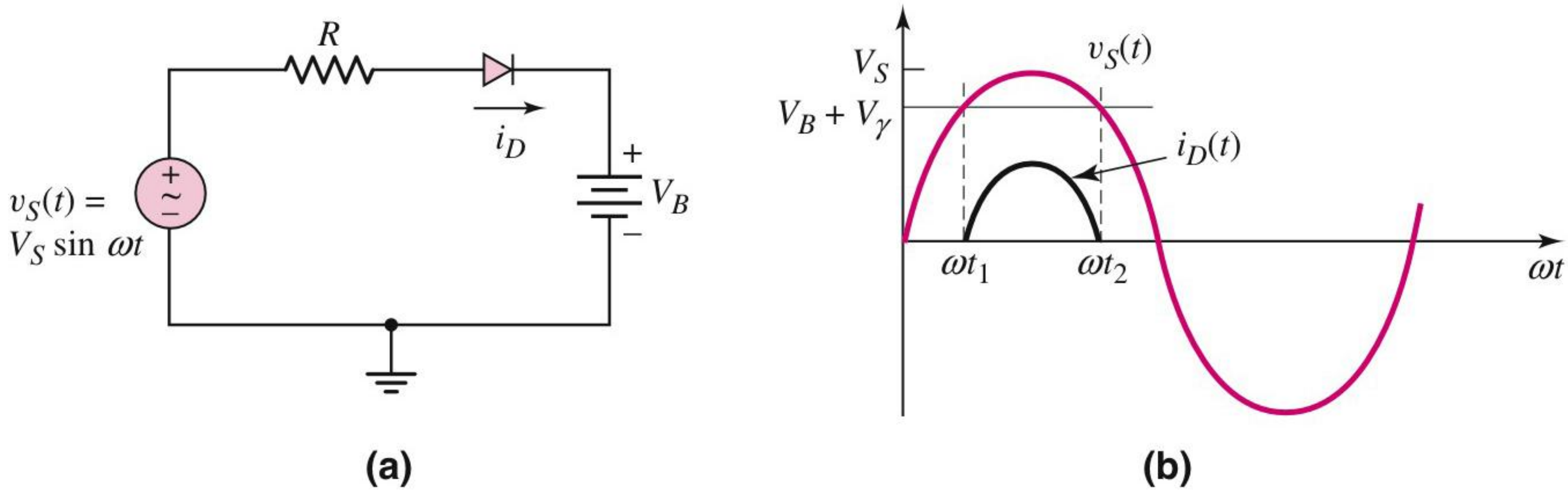


(a) (b)

As v_S varies with time, the load line also changes, which changes the Q-point (v_D and i_D) of the diode.

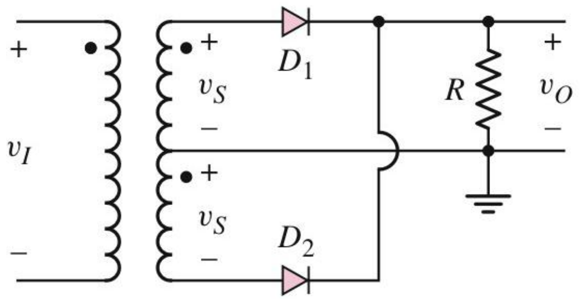
Half-wave Rectifier As Battery Charger

Half-Wave Rectifier as Battery Charger

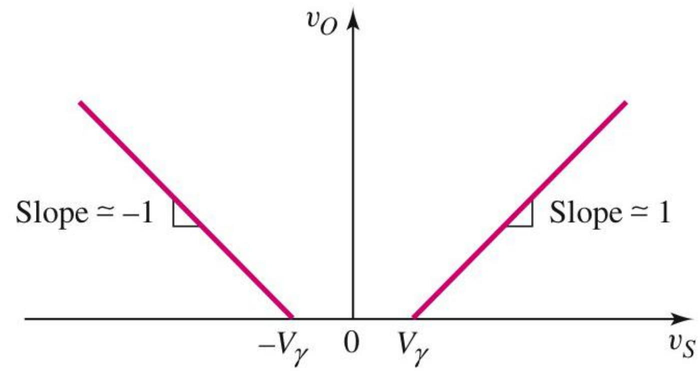


Full-wave Rectification

Full-Wave Rectifier

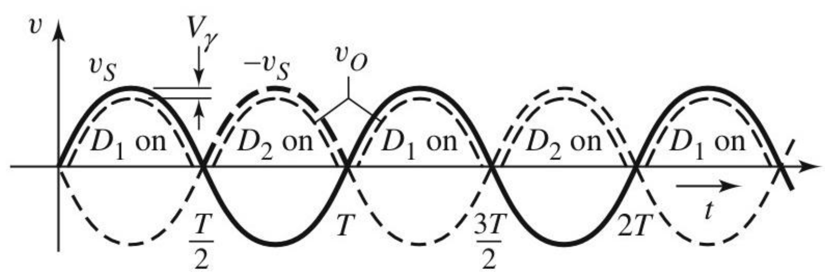


(a)



(b)

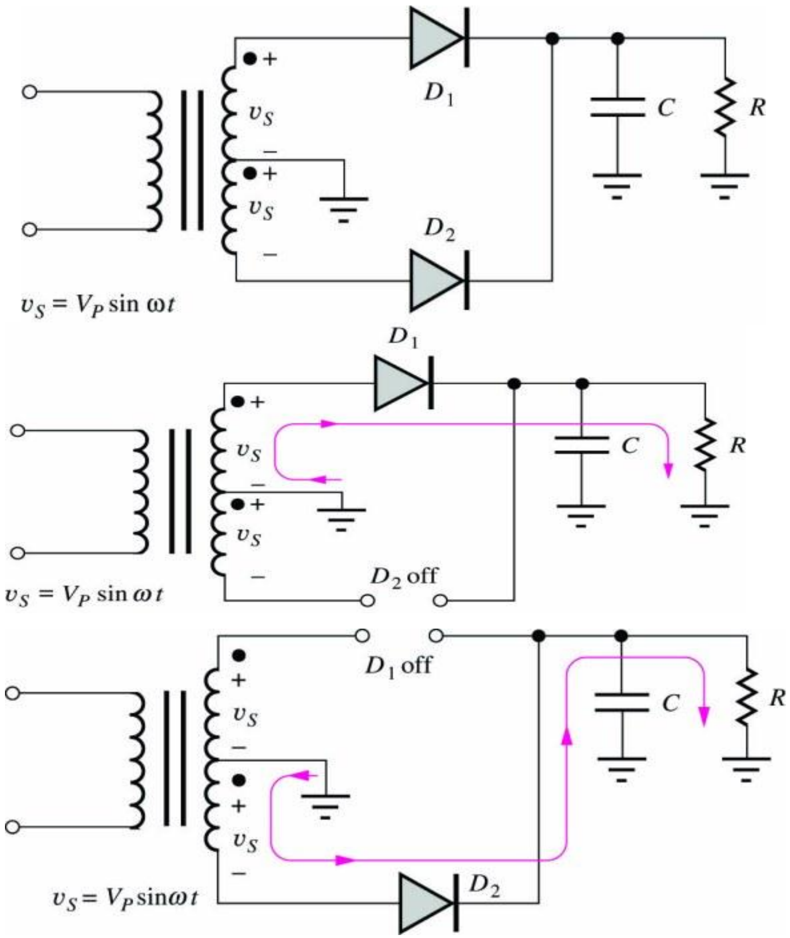
Voltage transfer characteristics

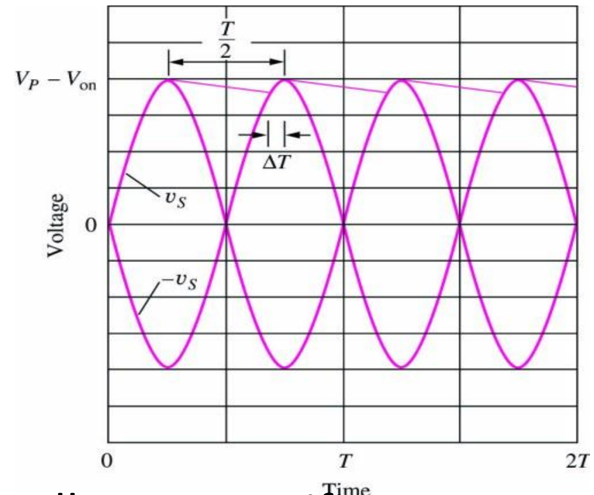


(c) Input and output waveforms

Two outputs from a center-tapped secondary winding that provides equal voltages with opposite polarities.

Full-Wave Rectifiers



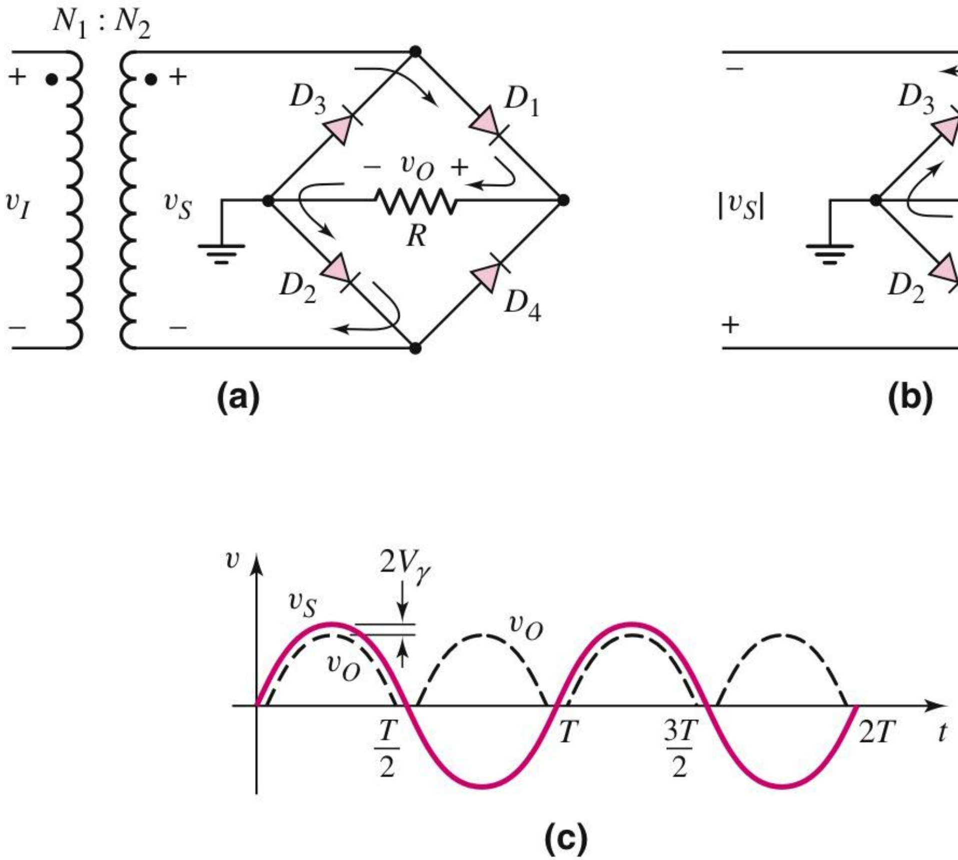


Full-wave rectifiers cut capacitor discharge time in half and require half the filter capacitance to achieve given ripple voltage. All specifications are same as for half-wave rectifiers.

Reversing polarity of diodes gives a full-wave rectifier with negative output voltage.

Full-Wave **Bridge** Rectifier

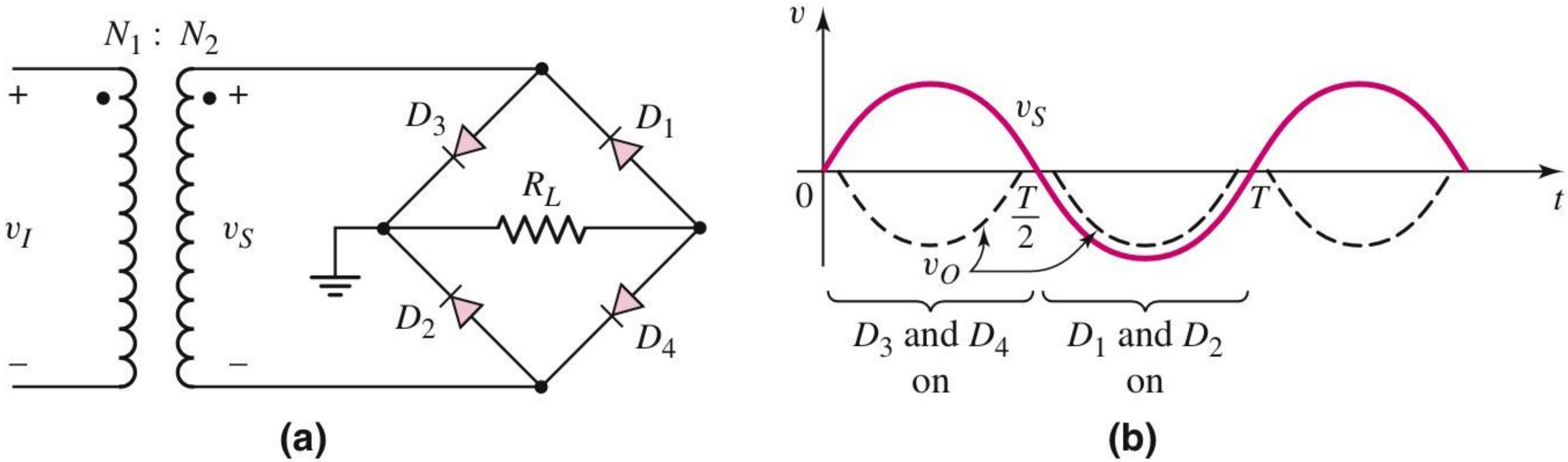
Full-Wave Bridge Rectifier



When v_S is positive, D_1 and D_2 are turned on (a). When v_S is negative, D_3 and D_4 are turned on (b). In either case, current flows through R in the same direction, resulting in an output voltage, v_O, shown in (c).

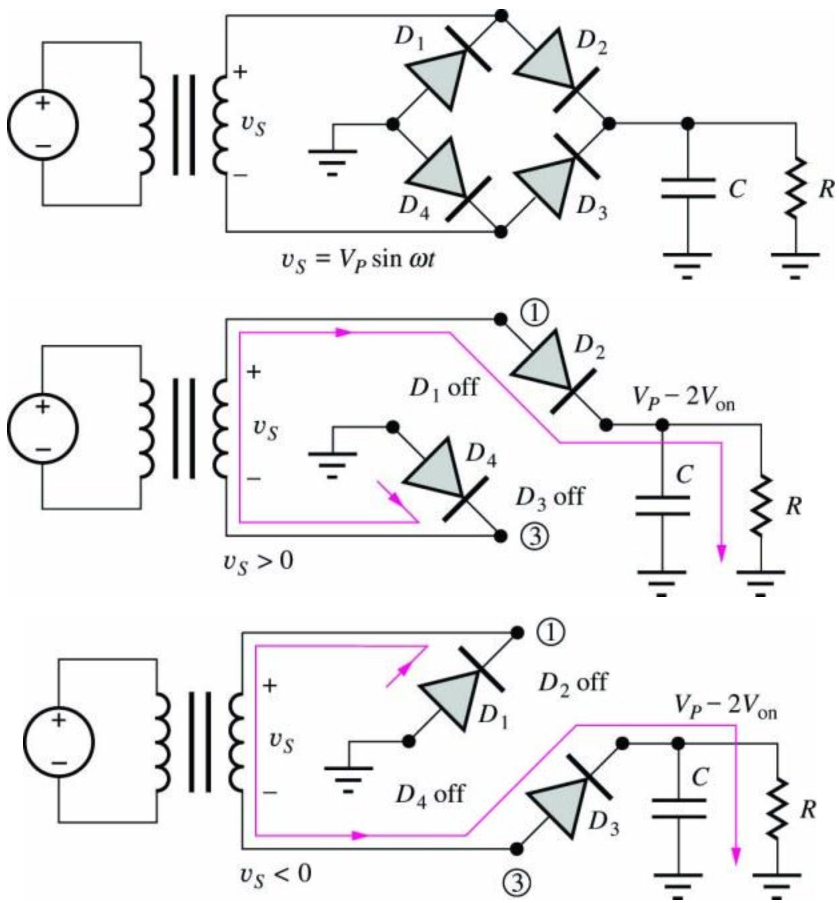
Do not require a center-tapped secondary winding!

Full-Wave Bridge Rectifier



The output voltage is now negative!

Full-Wave Bridge Rectification

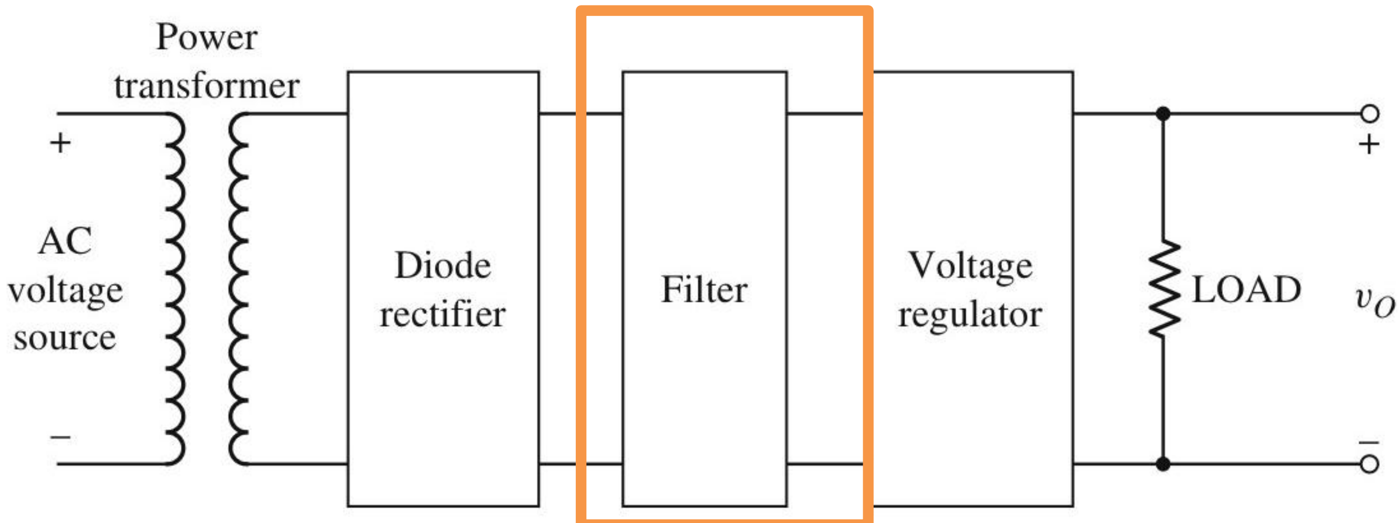


Requirement for a center-tapped transformer in the full-wave rectifier is eliminated through the use of 2 extra diodes. All other specifications are same as for a half-wave rectifier except PIV=V_P.

Filters

In signal processing, a filter is a device or process that removes some unwanted components or features from a signal.

Block Diagram for ac to dc Converter



The diode rectifier, filter, and voltage regulator are diode circuits.

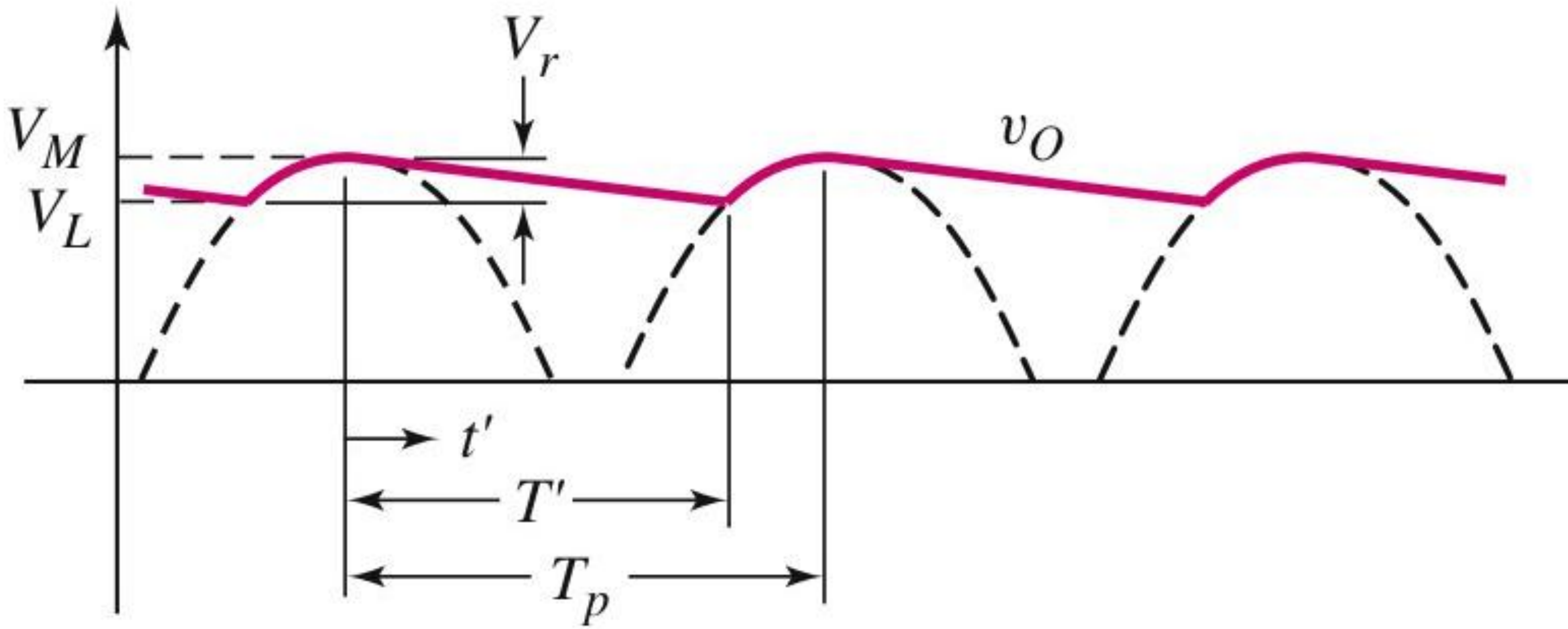
Rectifier Topology Comparison

- Filter capacitor is a major factor in determining cost, size and weight in design of rectifiers.

- For given ripple voltage, full-wave rectifier requires half the filter capacitance as that in half-wave rectifier. Reduced peak current can reduce heat dissipation in diodes. Benefits of full-wave rectification outweigh increased expenses and circuit complexity (a extra diode and center-tapped transformer).

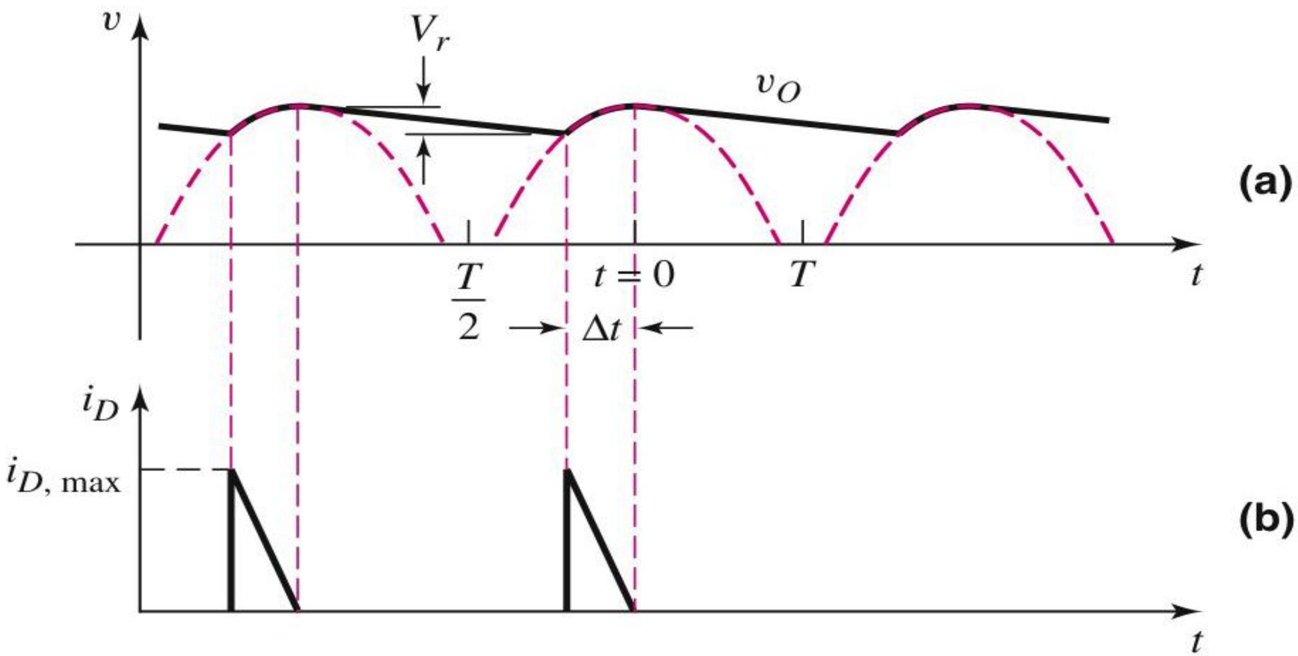
- Bridge rectifier eliminates center-tapped transformer, PIV rating of diodes is reduced. Cost of extra diodes is negligible.

Output Voltage of Full-Wave Rectifier with RC Filter



The ripple on the 'dc' output is $V_r = \dfrac{V_M}{2fRC}$ where $f = \dfrac{1}{2T_P}$

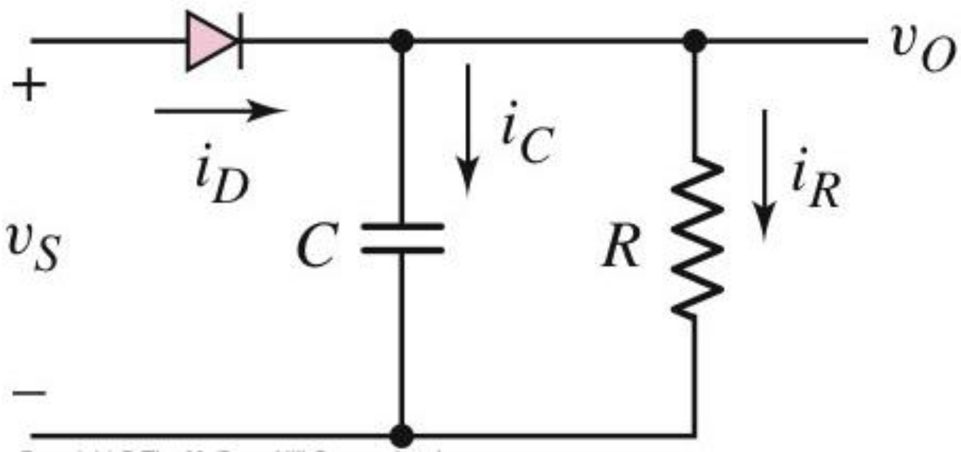
Output Voltage of Full-Wave Rectifier with RC Filter



$$\frac{\Delta t}{T} = \frac{1}{\pi}\sqrt{\frac{2V_r}{V_M}}$$

Diode conducts current for only a small portion of the period.

Equivalent Circuit During Capacitance Charging Cycle

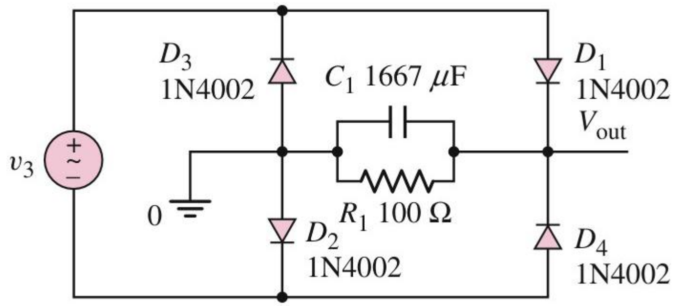


$$i_C = -\omega C V_M \omega t$$

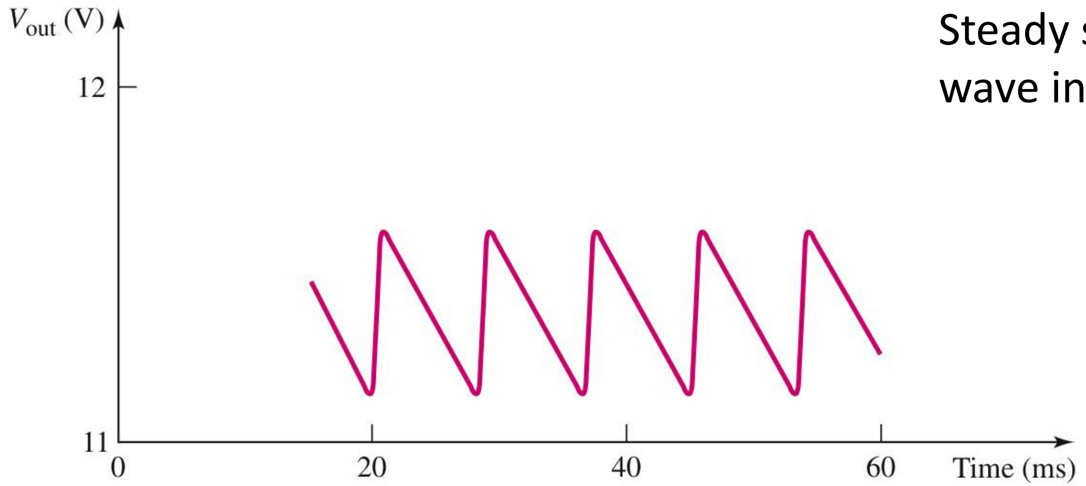
$$i_{C,peak} = +\omega C V_M \omega \Delta t$$

$$\omega \Delta t = \sqrt{\frac{2V_r}{V_M}}$$

PSpice Schematic of Diode Bridge Circuit



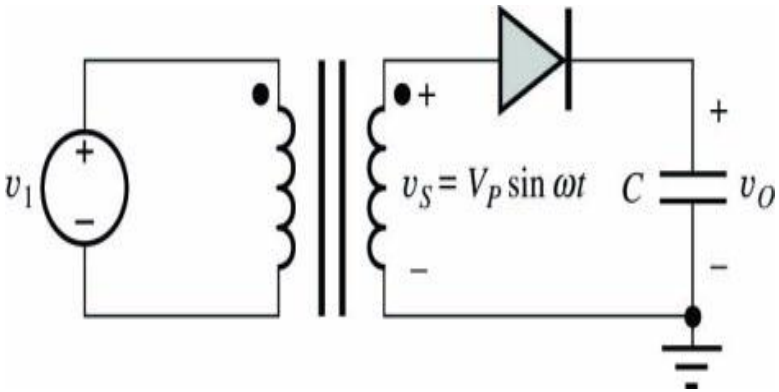
(a)

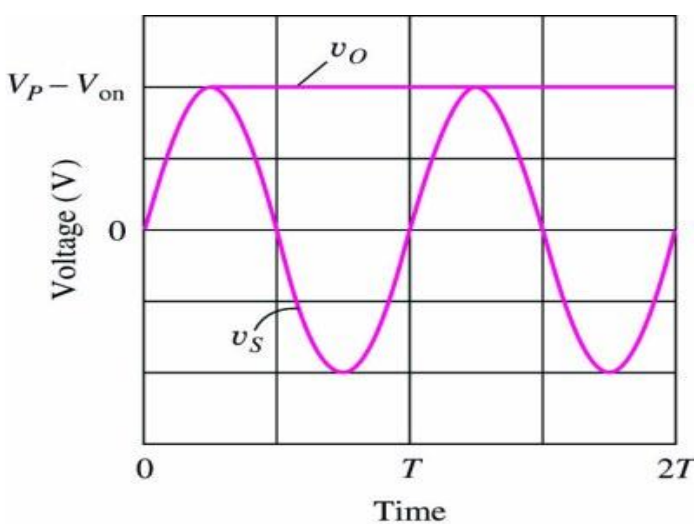


(b)

Steady state output voltage for a 60Hz sine wave input with peak value of 13.4V.

Rectifiers Applications: Peak Detector Circuit



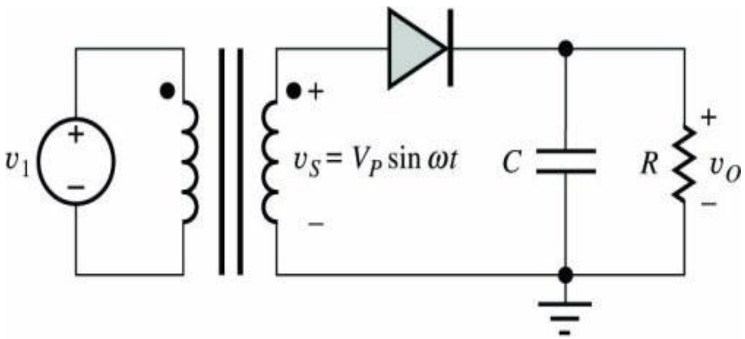


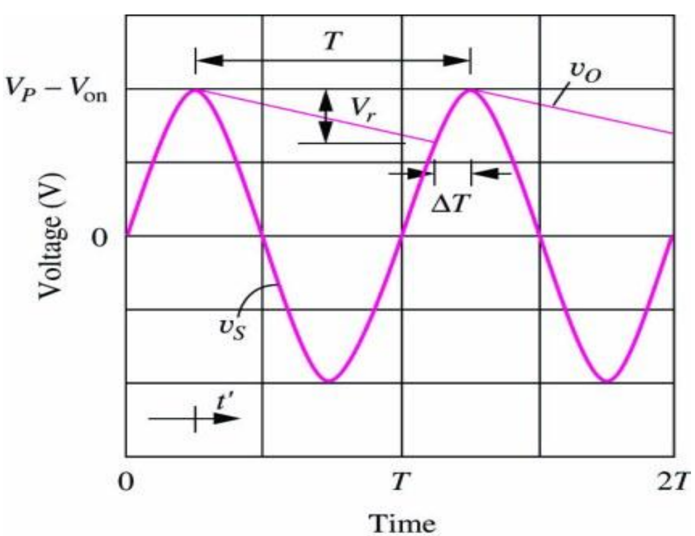
As input voltage rises, diode is on and capacitor (initially discharged) charges up to input voltage minus the diode voltage drop.

At peak of input, diode current tries to reverse, diode cuts off, capacitor has no discharge path and retains constant voltage providing constant output voltage

$V_{dc} = V_P - V_{on}$.

Half-Wave Rectifier Circuit with *RC* Load



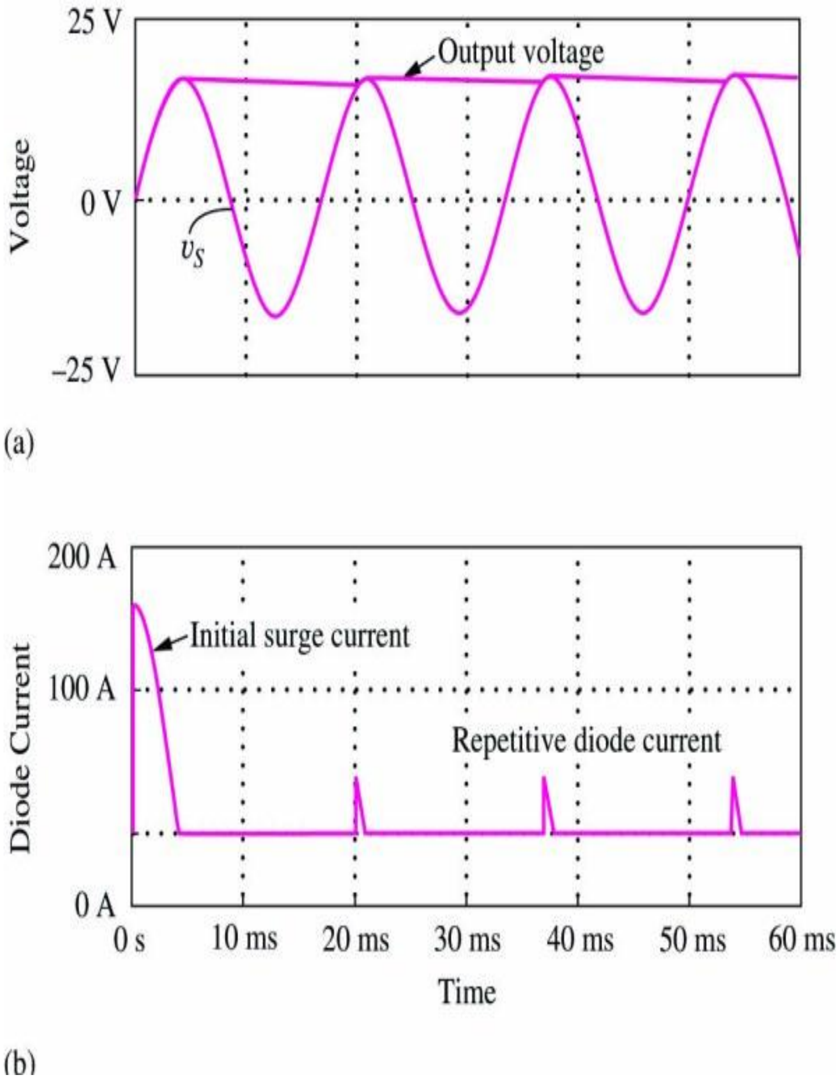


As input voltage rises during first quarter cycle, diode is on and capacitor (initially discharged) charges up to peak value of input voltage.

At peak of input, diode current tries to reverse, diode cuts off, capacitor discharges exponentially through *R*. Discharge continues till input voltage exceeds output voltage which occurs near peak of next cycle. Process then repeats once every cycle.

This circuit can be used to generate negative output voltage if the top plate of capacitor is grounded instead of bottom plate. In this case, $V_{dc} = -(V_P - V_{on})$

Peak Diode Current



In rectifiers, nonzero current exists in diode for only a very small fraction of period *T*, yet an almost constant dc current flows out of filter capacitor to load.

Total charge lost from capacitor in each cycle is replenished by diode during short conduction interval causing high peak diode currents. If repetitive current pulse is modeled as triangle of height I_P and width ΔT,

$$I_P = I_{dc}\frac{2T}{\Delta T} = 48.6A$$

using values from previous example.

Surge Current

Besides peak diode currents, when power supply is turned on, there is an even larger current through diode called **surge current.**

During first quarter cycle, current through diode is approximately

$$i_d(t) = i_C(t) \cong C\left(\frac{d}{dt}V_P \sin\omega t\right) = \omega C V_P \cos\omega t$$

Peak values of this initial surge current occurs at $t = 0^+$:

$$I_{SC} = \omega C V_P = 168\text{A}$$

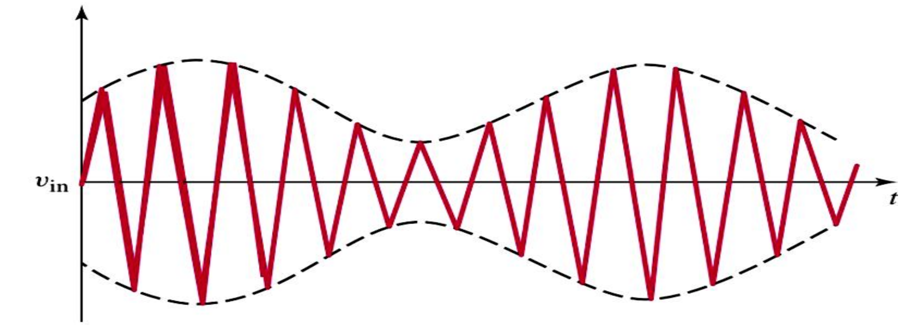
using values from previous example.

EEE103 would explain step response of RC circuits.

Actual values of surge current won't be as large as predicted because of neglected series resistance associated with rectifier diode as well as transformer.

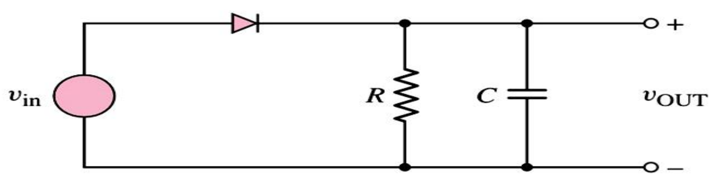
AM Signal Detector

Demodulation of Amplitude-Modulated Signal



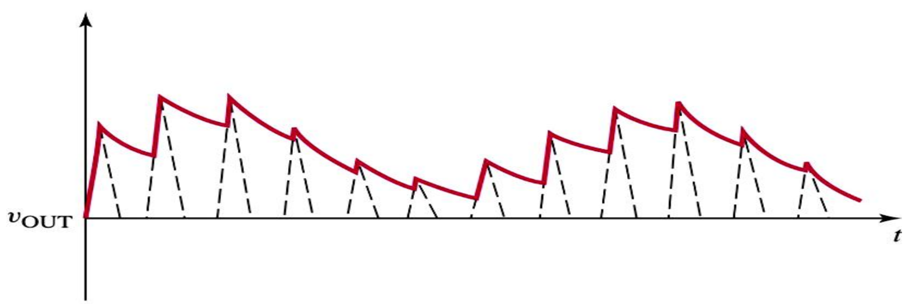
(a)

Modulated input signal



(b)

Detector circuit

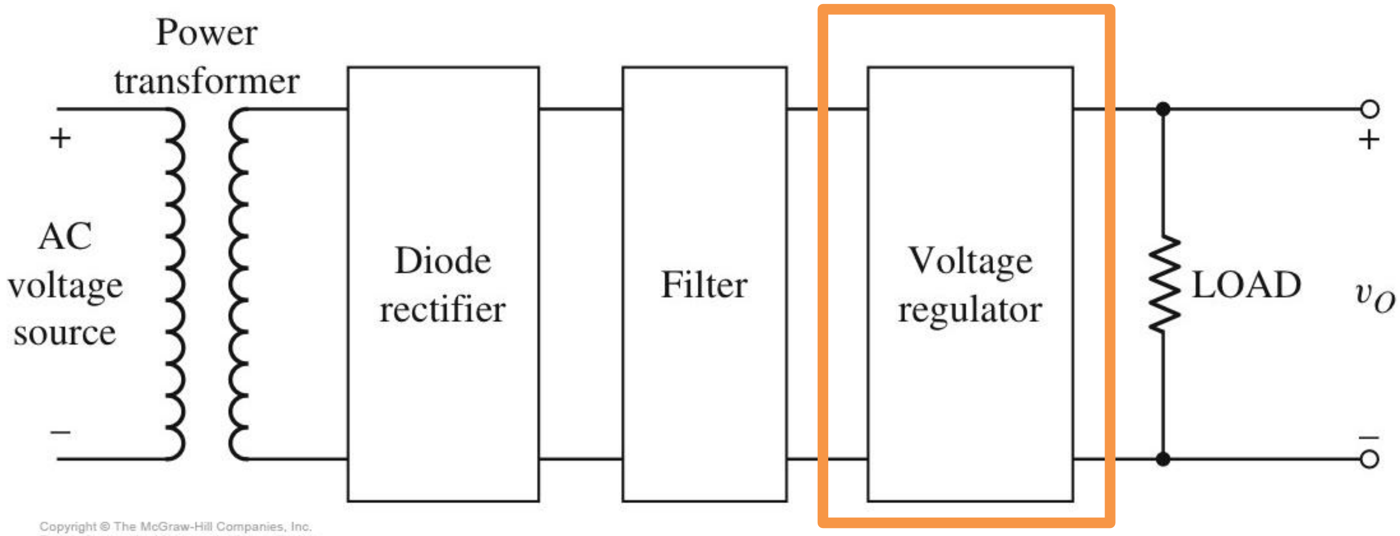


(c)

Demodulated output signal

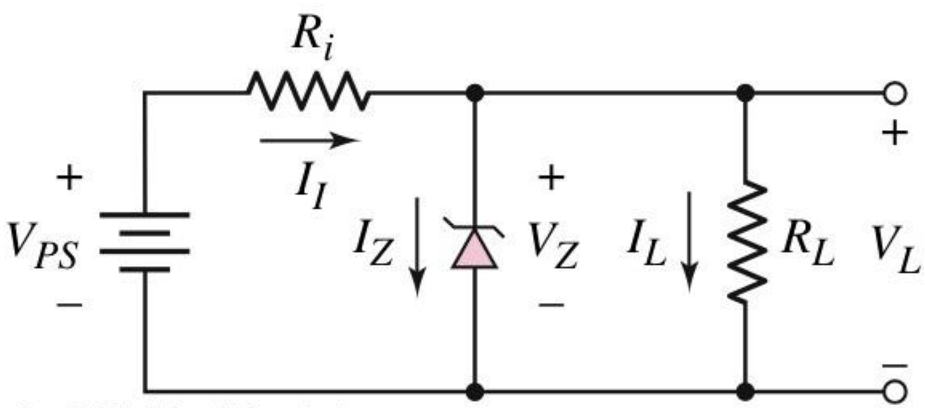
Zener Diode Circuits

Block Diagram for ac to dc Converter



The diode rectifier, filter, and voltage regulator are diode circuits.

Voltage Regulator



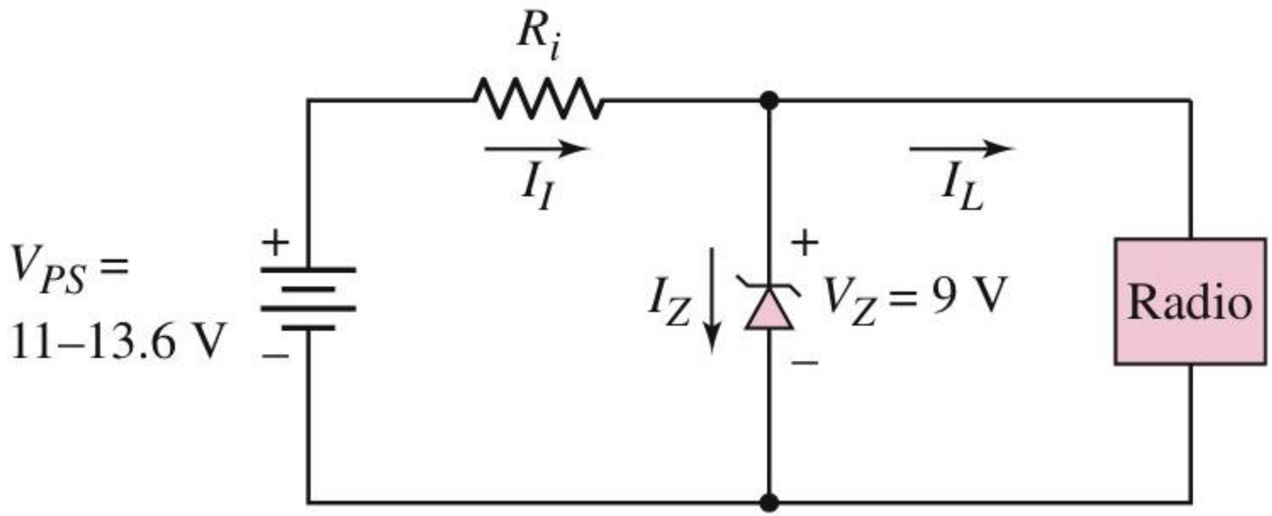
$$I_L = \frac{V_Z}{R_L}$$

$$I_I = \frac{V_{PS} - V_Z}{R_i}$$

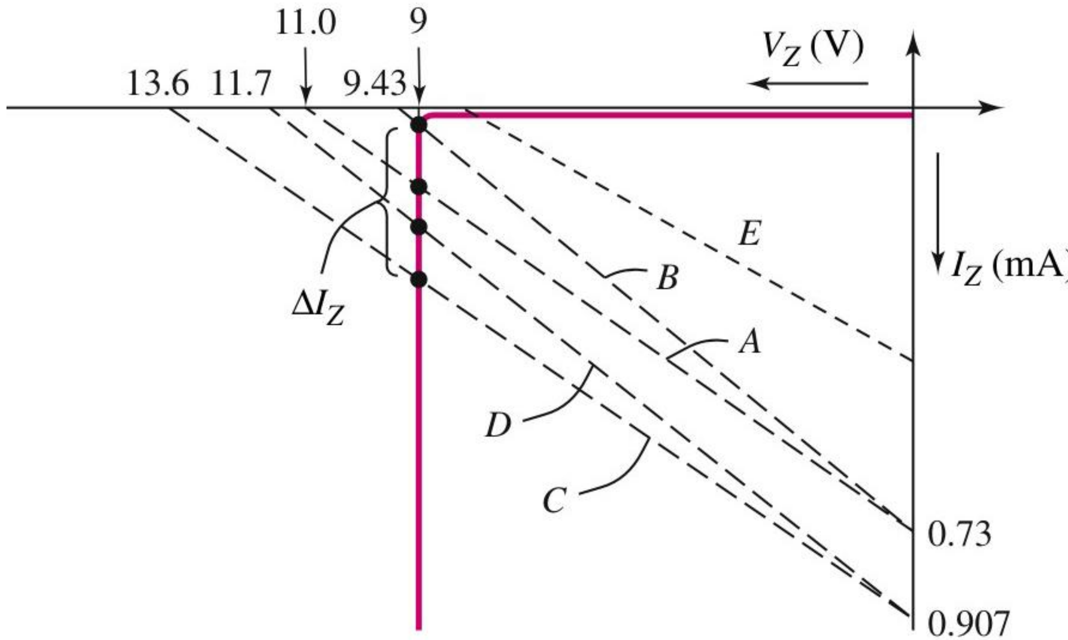
$$I_Z = I_I - I_L$$

The characteristics of the Zener diode determines V_L.

Design Example 2.5

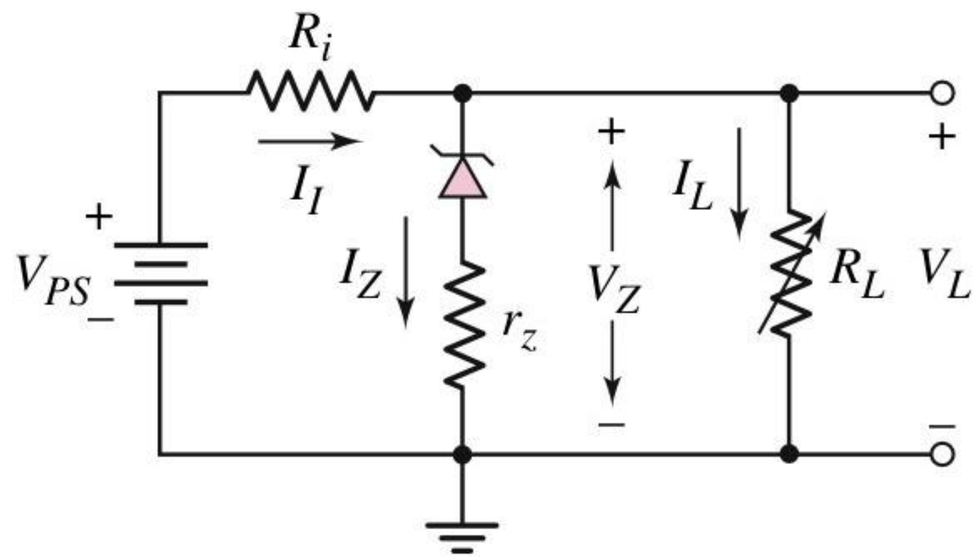


Load Line Analysis



The reverse bias I-V is important for Zener diodes.

Voltage Rectifier with nonzero Zener resistance



The Zener diode begins to conduct when $V_{PS} = V_Z$.

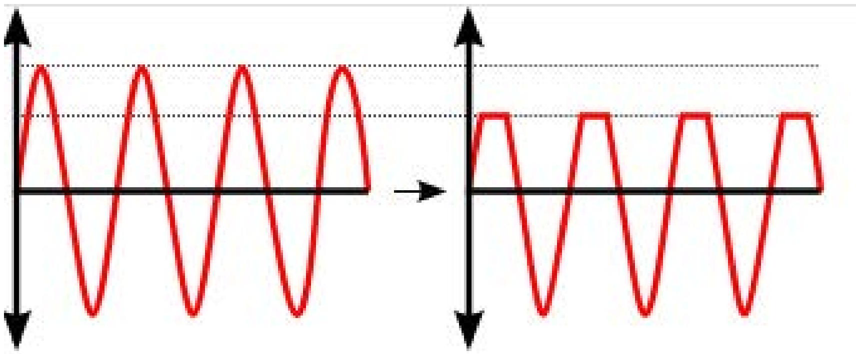
When $V_{PS} \geq V_Z$: $V_L = V_Z$

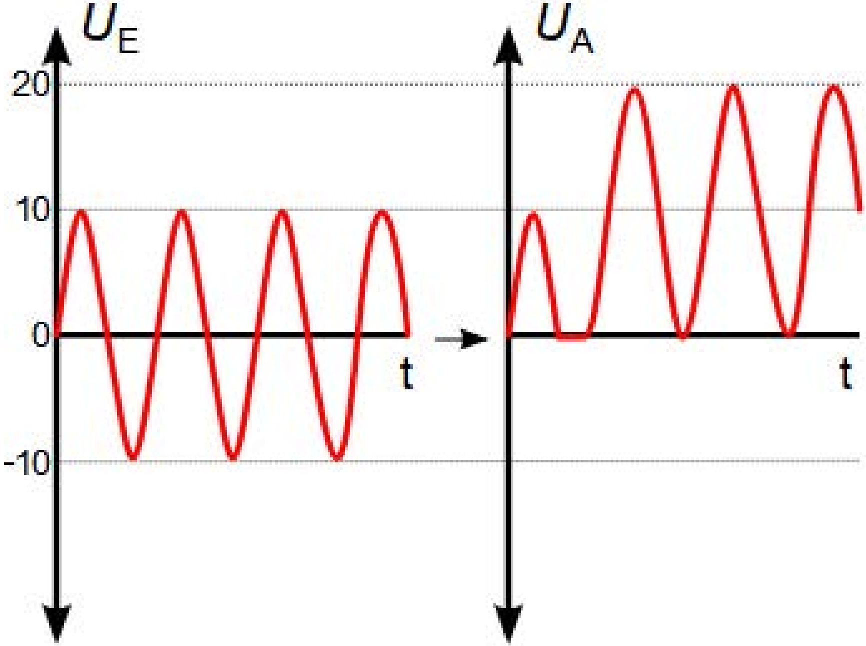
$I_L = V_Z/R_L$, but $V_Z \neq$ constant

$I_1 = (V_{PS} - V_Z)/R_i$

$I_Z = I_1 - I_L$

Clipper and Clamper Circuits

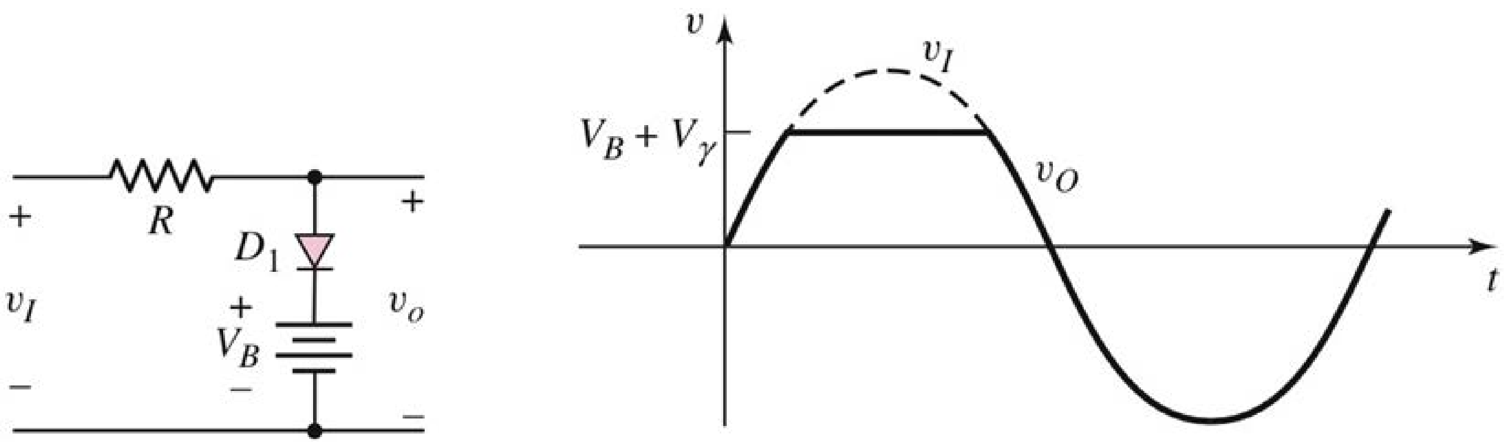




A **clipper** is a device designed to prevent the output of a circuit from exceeding a predetermined voltage level without distorting the remaining part of the applied waveform. (Series & Shunt)

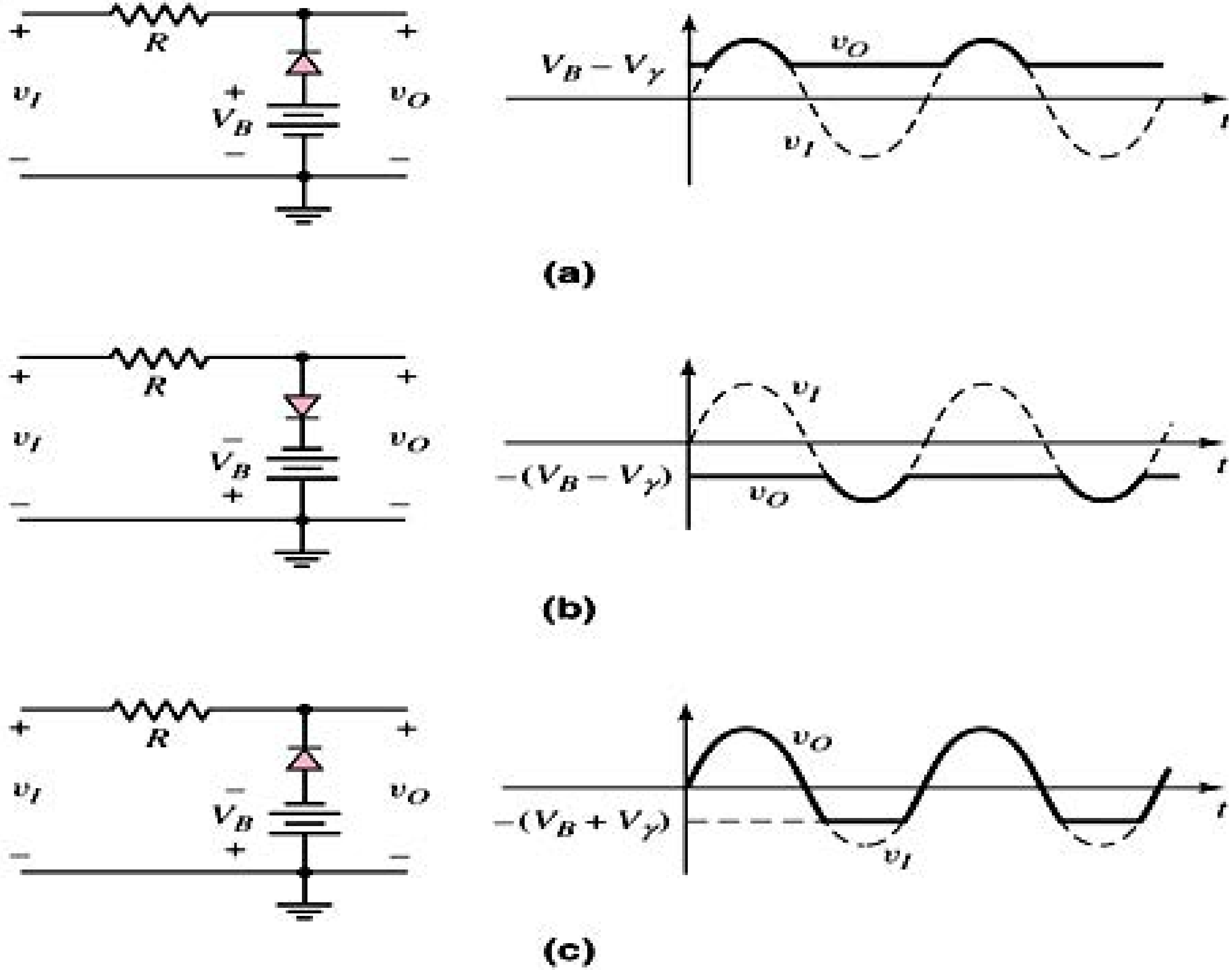
A **clamper** is an electronic circuit that fixes either the positive or the negative peak excursions of a signal to a defined value by shifting its DC value. Clamping circuits were common in analog television receivers.

Single Diode Clipper

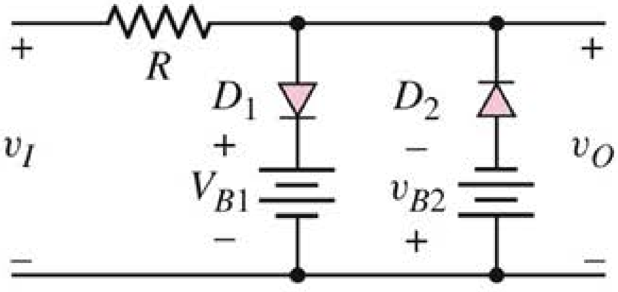


(a) (b)

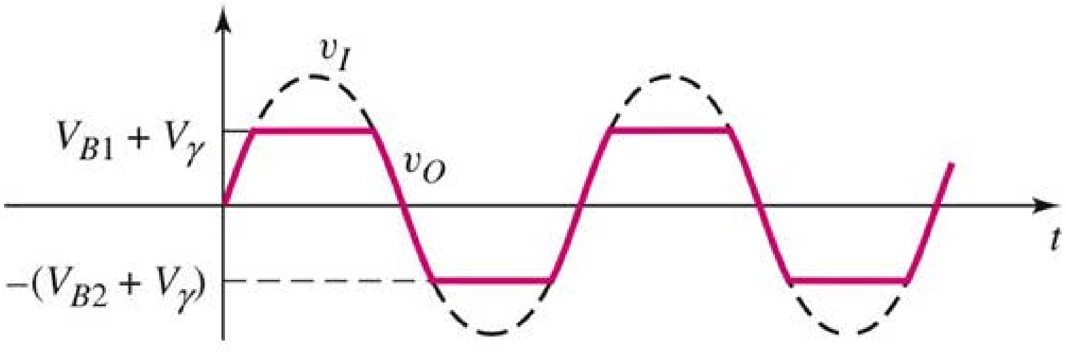
Additional Diode Clipper Circuits



Parallel-Based Diode Clipper Circuit

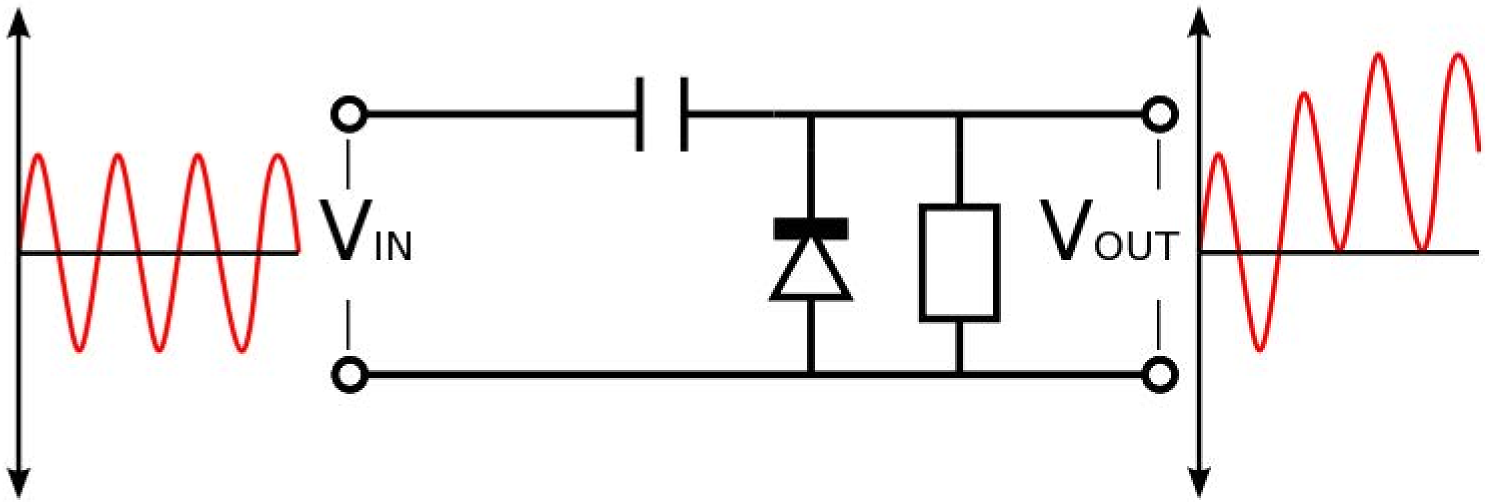


(a)



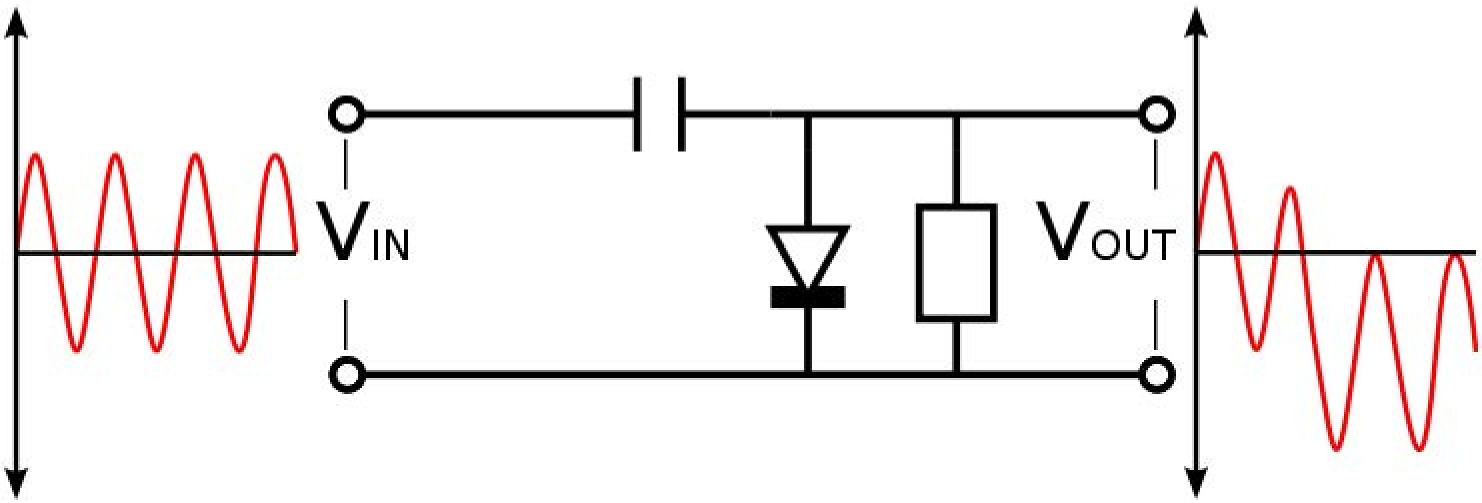
(b)

Positive Voltage Clamper Circuit



In the negative cycle of the input AC signal, the diode is forward biased and conducts, charging the capacitor to the peak negative value of VIN. During the positive cycle, the diode is reverse biased and thus does not conduct. The output voltage is therefore equal to the voltage stored in the capacitor plus the input voltage, so VOUT = VIN + VINpeak. This is also called a Villard circuit.

Negative Voltage Clamper Circuit



A negative unbiased clamp is the opposite of the equivalent positive clamp. In the positive cycle of the input AC signal, the diode is forward biased and conducts, charging the capacitor to the peak positive value of VIN. During the negative cycle, the diode is reverse biased and thus does not conduct. The output voltage is therefore equal to the voltage stored in the capacitor plus the input voltage again, so VOUT = VIN - VINpeak

Impedance

- **Electrical impedance** is the measure of the opposition that a circuit presents to a current when a voltage is applied.

- Impedance extends the concept of resistance to AC circuits, and possesses both magnitude and phase, unlike resistance, which has only magnitude.

Impedance (Cont')

- In Cartesian form,

$$Z = R + jX$$

where the real part of impedance is the resistance R, and the imaginary part is the reactance X. j is the imaginary unit and there is $j^2 = -1$.

What is reactance?

Reactance

- The concept of impedance in AC circuits involves **TWO** additional **impeding mechanisms** compared to the normal *resistance* of DC circuits:

1. the induction of voltages in conductors self-induced by the magnetic fields of currents – *inductance, and*
2. the electrostatic storage of charge induced by voltages between conductors – *capacitance.*

- The impedance caused by these two effects is **collectively** referred to as reactance.

Reactance (Cont')

- The impedance of inductors increases as frequency increases

$$Z_L = j\omega L$$

- The impedance of capacitors decreases as frequency increases

$$Z_C = \frac{1}{j\omega C}$$

Capacitance

$$i_{\mathrm{C}}(t) = C\frac{\mathrm{d}\,v_{\mathrm{C}}(t)}{\mathrm{d}\,t}$$

$$v_{\mathrm{C}}(t) = V_p \sin(\omega t)$$

$$\frac{\mathrm{d}\,v_{\mathrm{C}}(t)}{\mathrm{d}\,t} = \omega V_p \cos(\omega t)$$

$$\frac{v_{\mathrm{C}}\,(t)}{i_{\mathrm{C}}\,(t)} = \frac{V_p \sin(\omega t)}{\omega V_p C \cos(\omega t)} = \frac{\sin(\omega t)}{\omega C \sin\left(\omega t + \frac{\pi}{2}\right)}$$

$$Z_{\mathrm{capacitor}} = \frac{1}{\omega C} e^{-j\frac{\pi}{2}}$$

$$Z_{\mathrm{capacitor}} = -j\frac{1}{\omega C} = \frac{1}{j\omega C}$$

Inductance

$$v_{\mathrm{L}}(t) = L\frac{\mathrm{d}\, i_{\mathrm{L}}(t)}{\mathrm{d}\, t}$$

$$i_{\mathrm{L}}(t) = I_p \sin(\omega t)$$

$$\frac{\mathrm{d}\, i_{\mathrm{L}}(t)}{\mathrm{d}\, t} = \omega I_p \cos\left(\omega t\right)$$

$$\frac{v_{\mathrm{L}}\left(t\right)}{i_{\mathrm{L}}\left(t\right)} = \frac{\omega I_p L \cos(\omega t)}{I_p \sin\left(\omega t\right)} = \frac{\omega L \sin\left(\omega t + \frac{\pi}{2}\right)}{\sin(\omega t)}$$

$$Z_{\text{inductor}} = \omega L e^{j\frac{\pi}{2}}$$

$$Z_{\text{inductor}} = j\omega L$$

Inductance

$$v_{\mathrm{L}}(t) = L\frac{\mathrm{d}\, i_{\mathrm{L}}(t)}{\mathrm{d}\, t}$$

$$i_{\mathrm{L}}(t) = I_p \sin(\omega t)$$

$$\frac{\mathrm{d}\, i_{\mathrm{L}}(t)}{\mathrm{d}\, t} = \omega I_p \cos(\omega t)$$

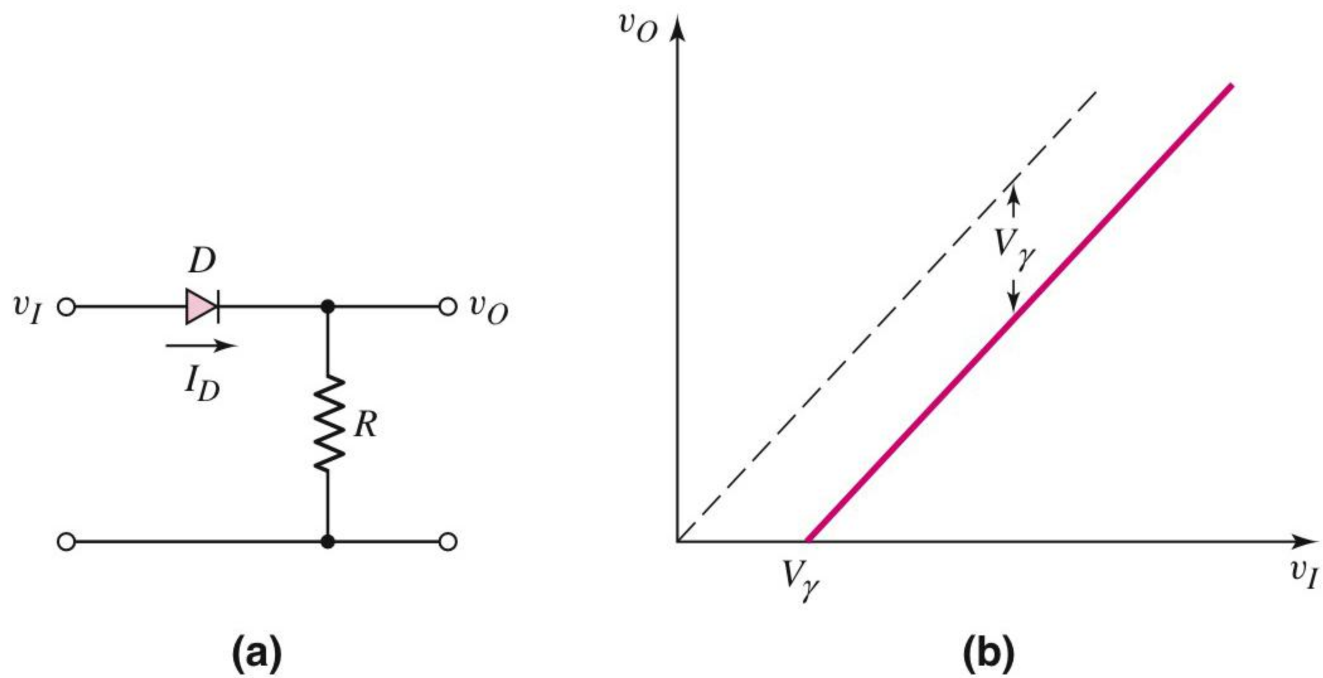
$$\frac{v_{\mathrm{L}}(t)}{i_{\mathrm{L}}(t)} = \frac{\omega I_p L \cos(\omega t)}{I_p \sin(\omega t)} = \frac{\omega L \sin\left(\omega t + \frac{\pi}{2}\right)}{\sin(\omega t)}$$

$$Z_{\text{inductor}} = \omega L e^{j\frac{\pi}{2}}$$

$$Z_{\text{inductor}} = j\omega L$$

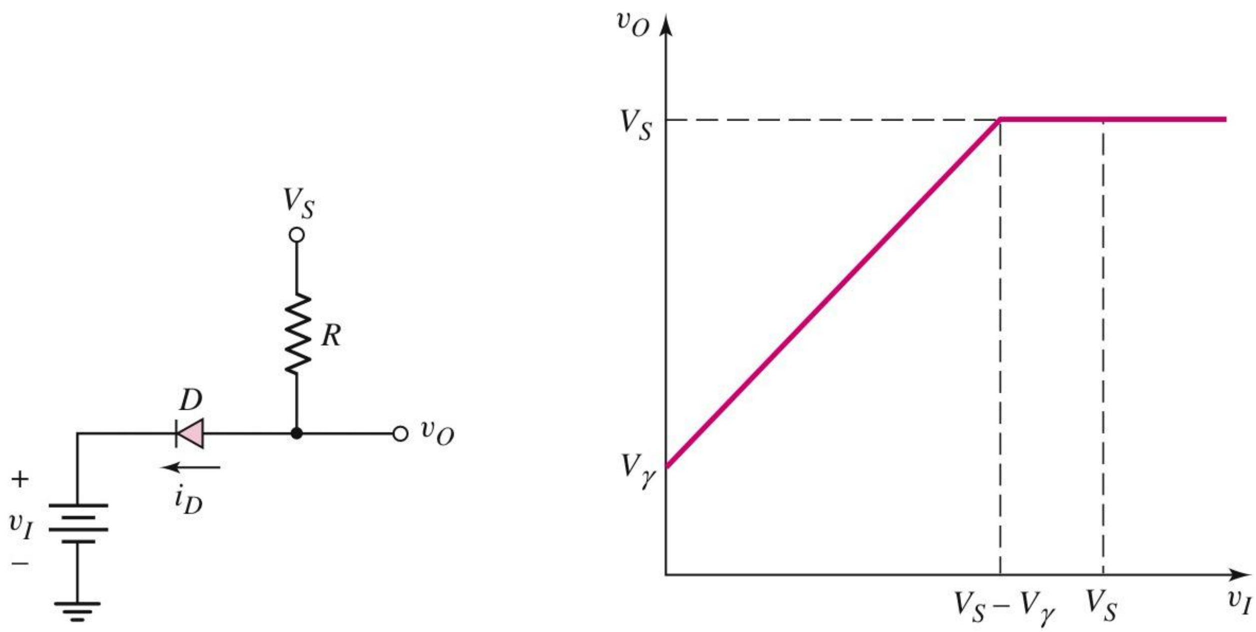
Example Diode Circuits

Diode and Resistor In Series



Voltage shift between input and output voltages in transfer characteristics is because the diode only conducts when $v_1 \geq V_\gamma$.

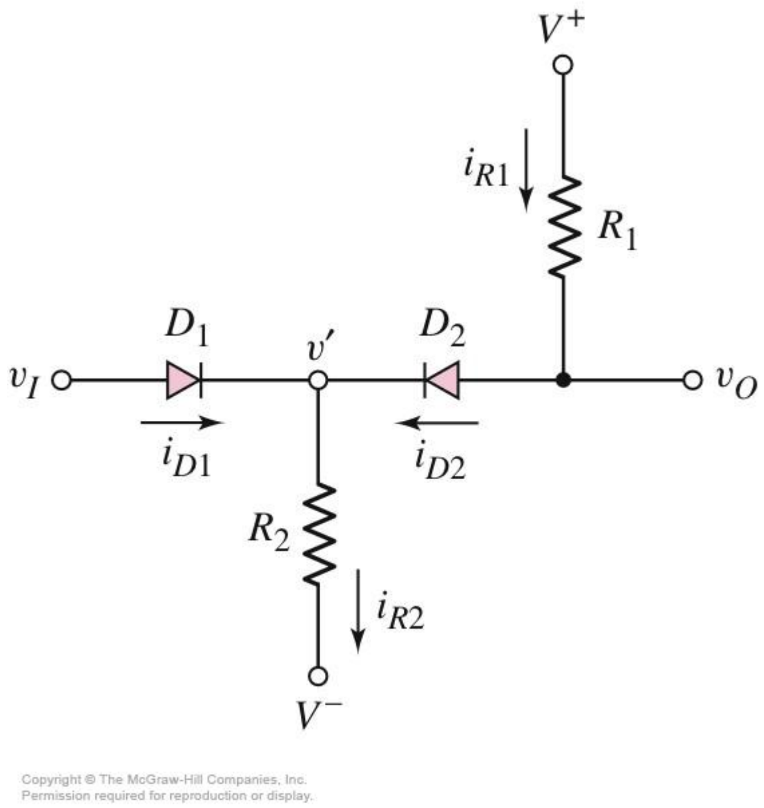
Diode with Input Voltage Source

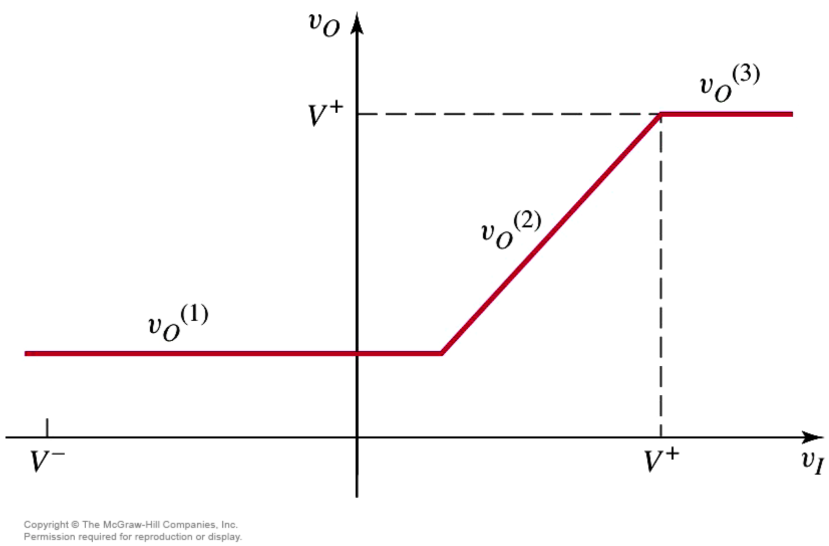


(a) (b)

Output voltage is a constant when the diode is not conducting, when $v_1 \geq V_s$ - V_γ.

2 Diode Circuit



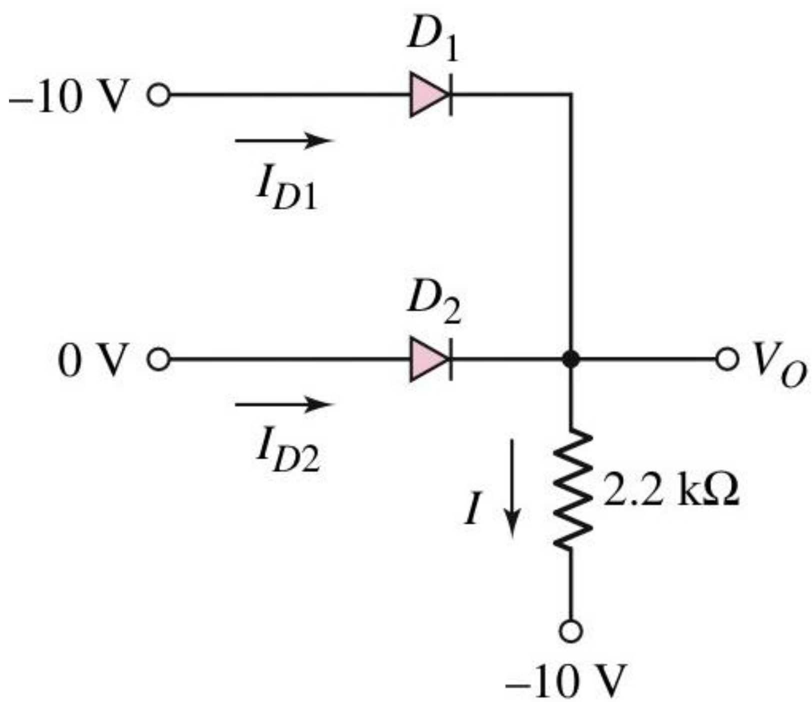


Voltage transfer characteristics

Problem-Solving Technique: Multiple Diode Circuits

1. Assume the state of the diode.
   a. If assumed on, $V_D = V_\gamma$
   b. If assumed off, $I_D = 0$.
2. Analyze the 'linear' circuit with assumed diode states.
3. Evaluate the resulting state of each diode.
4. If any initial assumptions are proven incorrect, make new assumption and return to Step 2.

Exercise problem

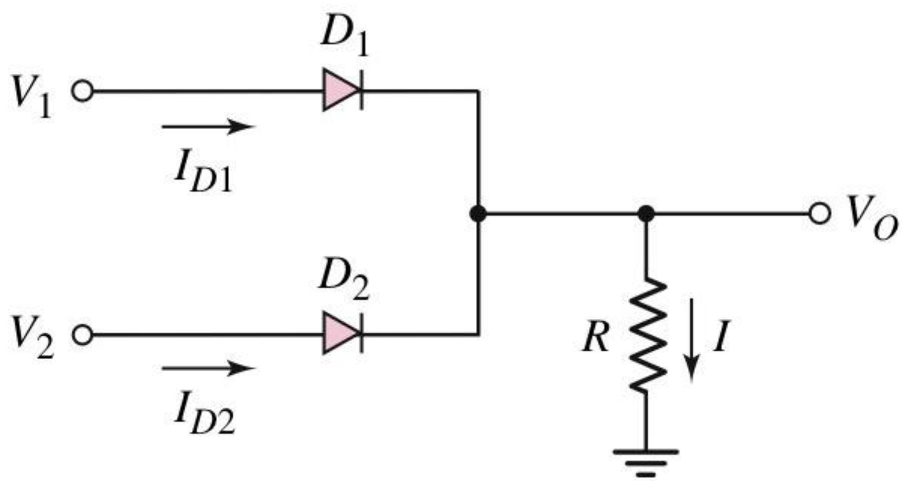


D_1 is not on.

D_2 is on.
This pins V_O to -0.6V

Diode Logic Circuits

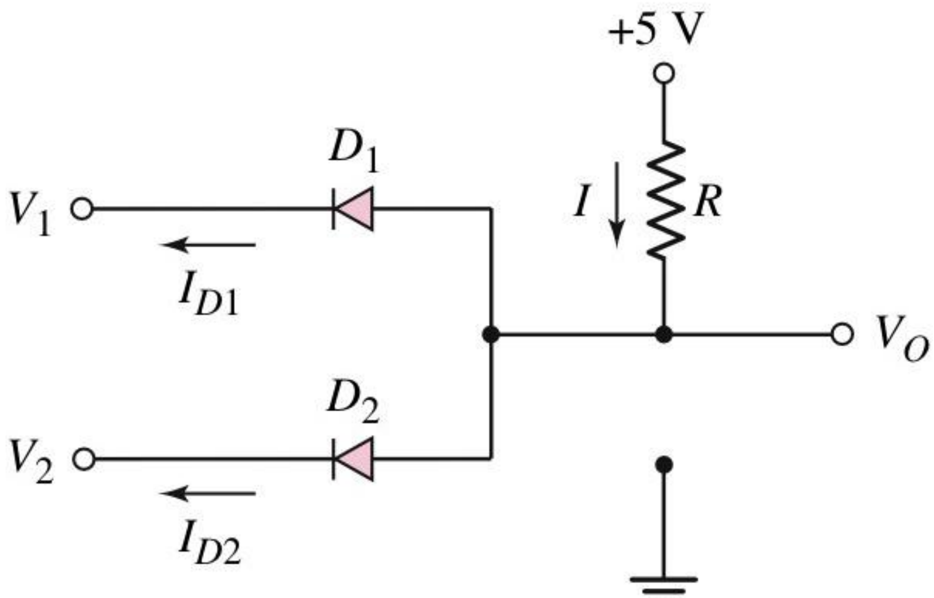
Diode Logic Circuits: 2-Input OR Gate



V_1 (V)	V_2 (V)	V_O (V)
0	0	0
5	0	4.3
0	5	4.3
5	5	4.3

$V_\gamma = 0.7V$

Diode Logic Circuits: 2-Input AND Gate

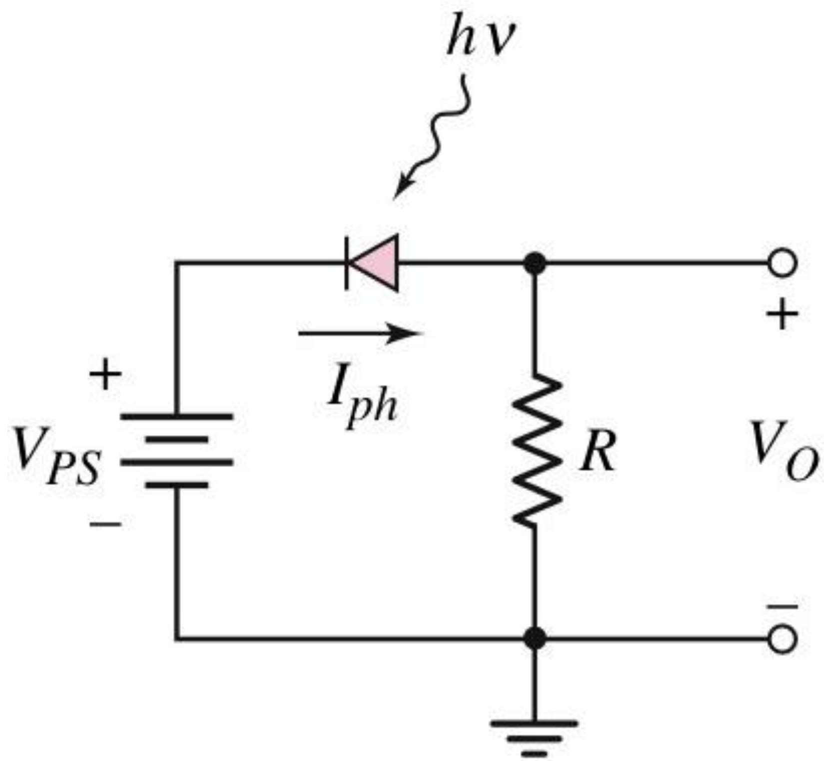


V_1 (V)	V_2 (V)	V_O (V)
0	0	0
5	0	0
0	5	0
5	5	4.3

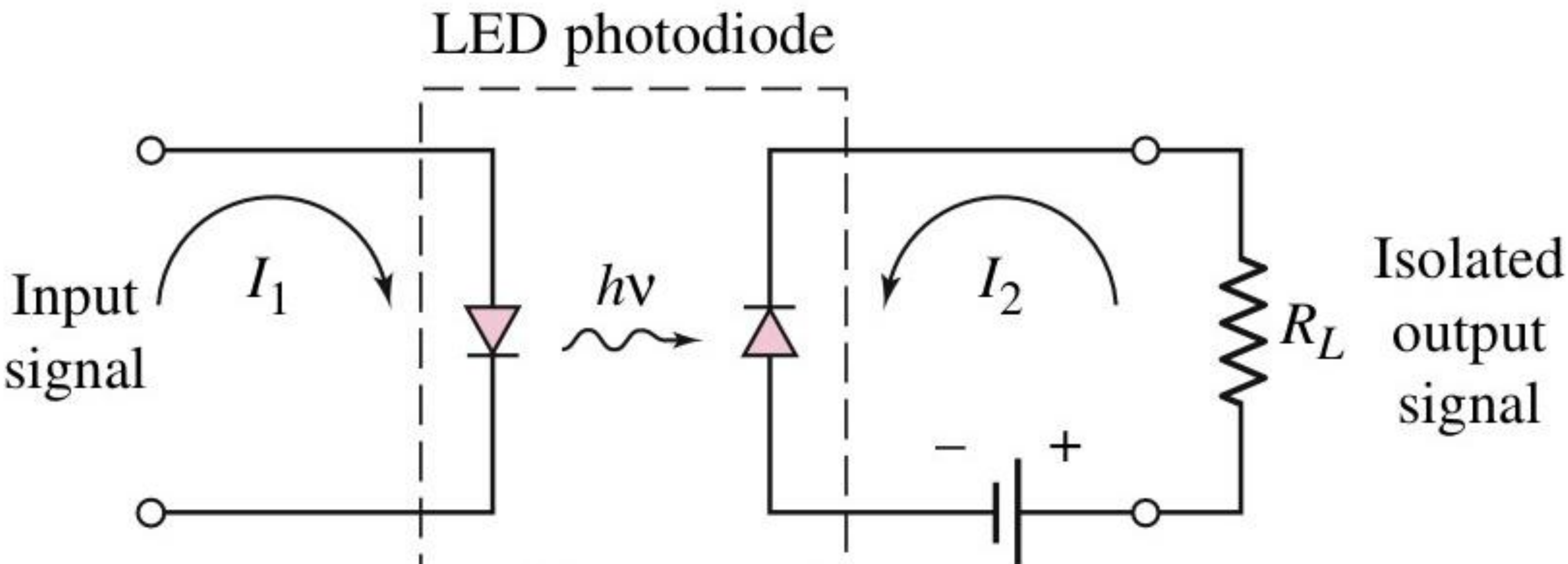
$V_\gamma = 0.7V$

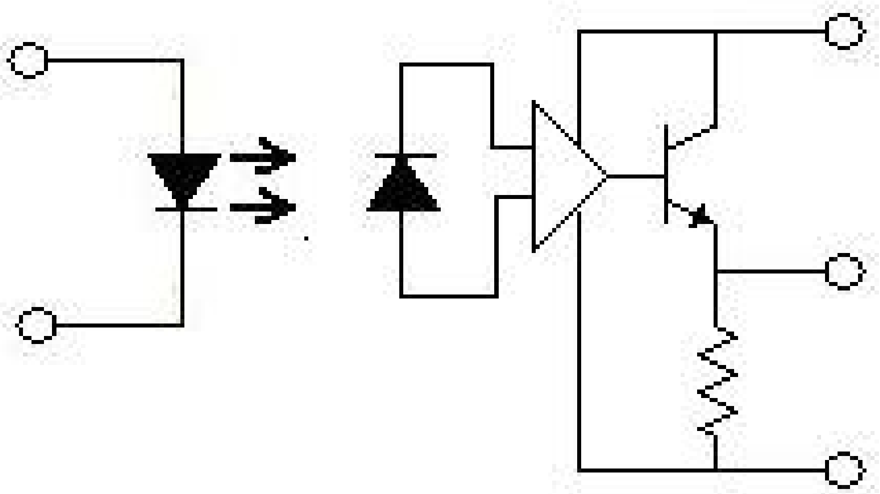
Photodiode and LED Circuits

Photodiode Circuit



Optoisolator



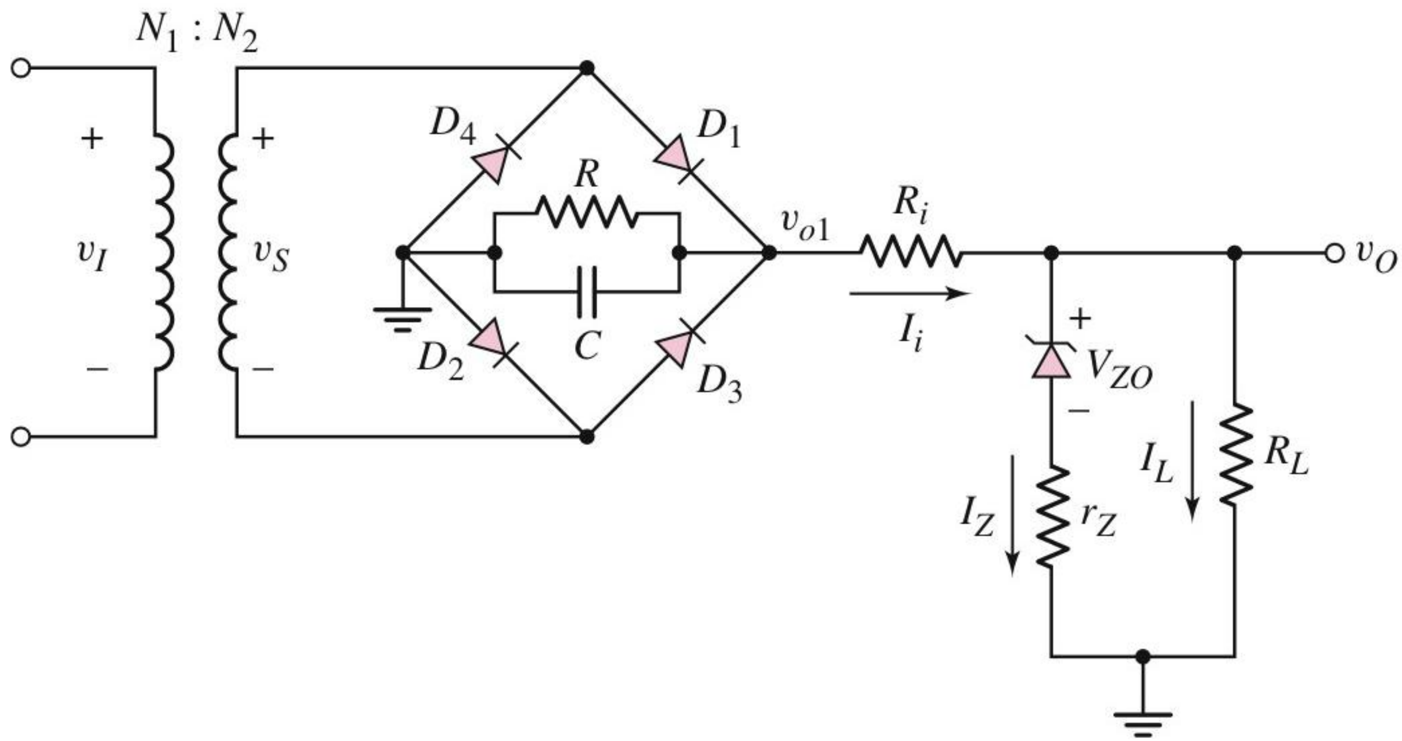


Optoisolator has been widely used in electronic devices of industry automation.

Design Application

- DC Power Supply

Design DC Power Supply Circuit



Chapter 2 Summary

1. Determine the operation and characteristics of diode rectifier circuits, which is the first stage of the process of converting an ac signal into a dc signal in the electronic power supply.

2. Apply the characteristics of the Zener diode to a Zener diode voltage regulator circuit.

3. Apply the nonlinear characteristics of diodes to create waveshaping circuits known as clippers and clampers.

4. Examine the techniques used to analyze circuits that contain more than one diode.

5. Understand the operation and characteristics of specialized photodiode and light-emitting diode circuits.