PN-Junction Diode

Applications

Outline

- Analysis of Diode Circuit
  - Models
    - Circuit model
- Applications of diode
  - Rectification
    - Half wave Rectifiers
    - Full wave Rectifiers
      - Centre-tap
      - Bridge
  - Filtration
  - Voltage Regulators
    - Zener Diode

Diode Circuits

Diodes as Circuit Elements

- Ideal Diode
- Circuit Characteristics
- Actual Diode

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Applications

- Regulators
- Rectifiers
- Limiting and Clamping Circuits

- After we have studied in detail the physics of a diode, it is time to study its behavior as a circuit element and its many applications.

The Diode Models

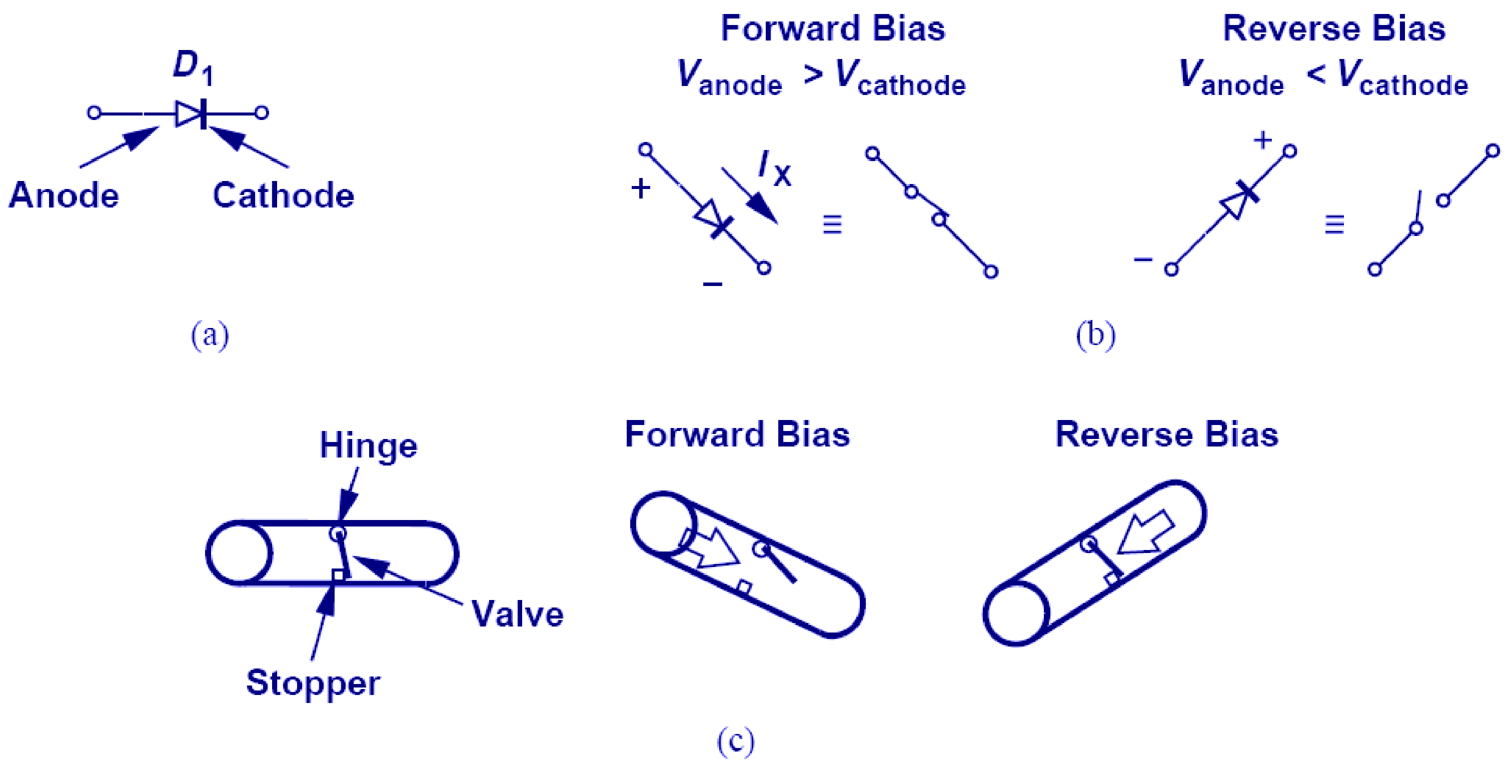
Circuit Model

a) Simplified diode model

b) The constant-voltage-drop model

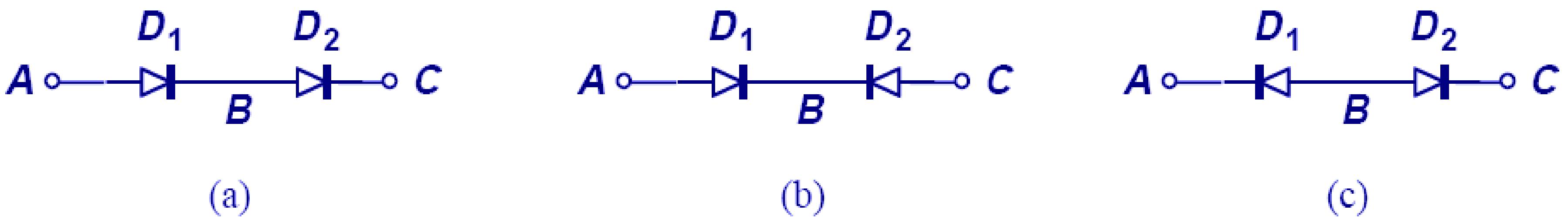
c) Zener Diode Model

Ideal Diode



- In an ideal diode, if the voltage across it tends to exceed zero, current flows.
- It is analogous to a water pipe that allows water to flow in only one direction.

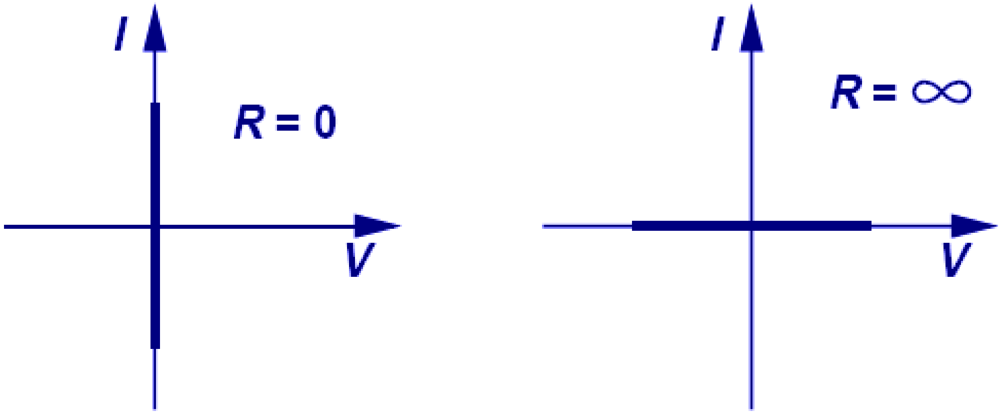
Diodes in Series



- Diodes cannot be connected in series randomly. For the circuits above, only a) can conduct current from A to C.

IV Characteristics of an Ideal Diode

$$R = 0 \Rightarrow I = \frac{V}{R} = \infty \qquad R = \infty \Rightarrow I = \frac{V}{R} = 0$$



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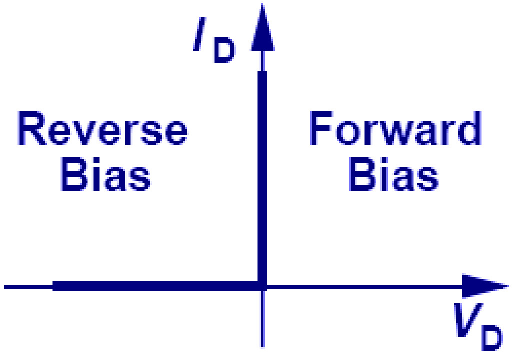
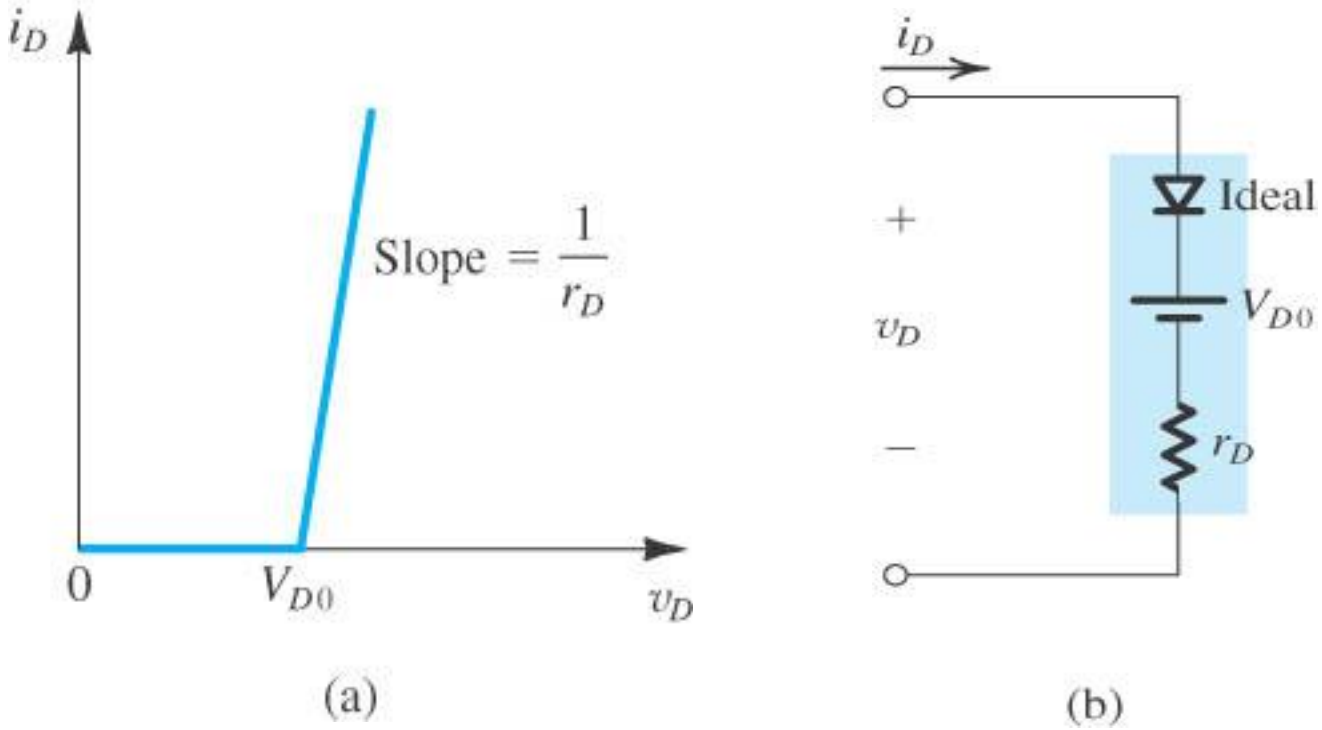


(b)

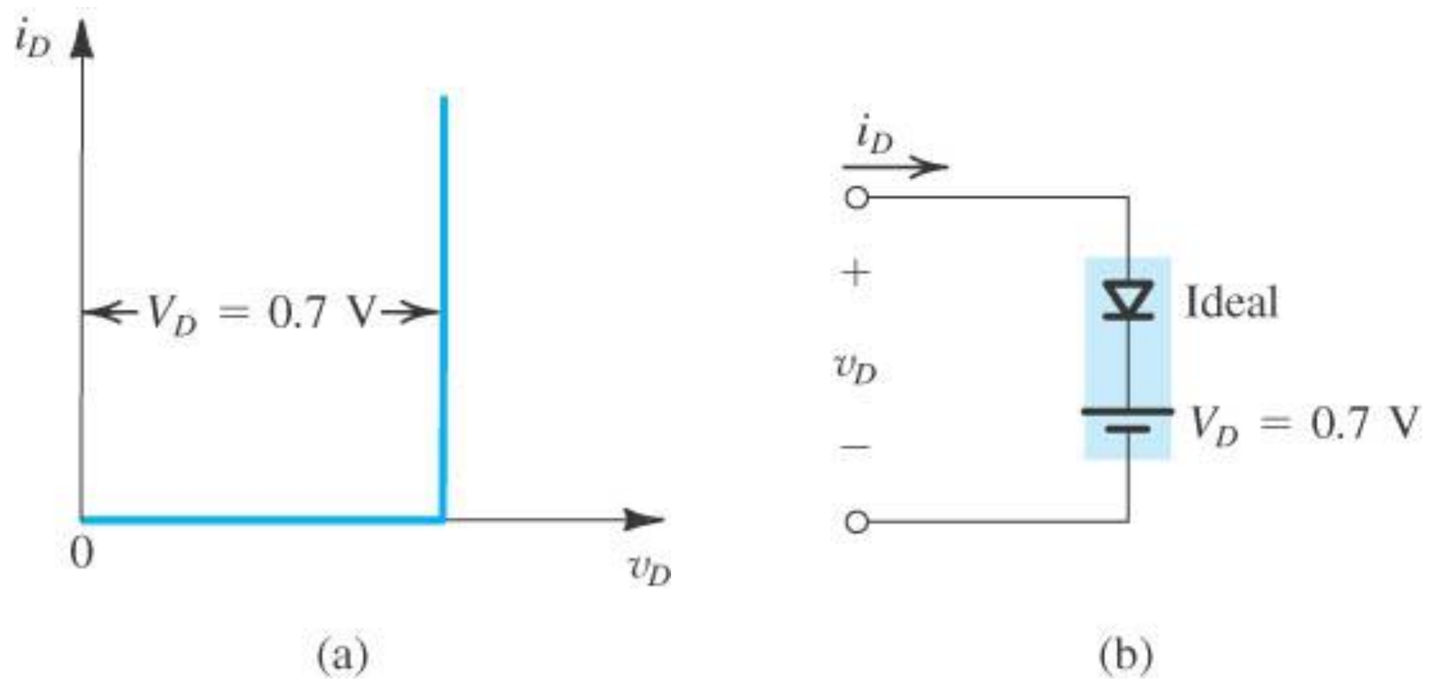
- If the voltage across anode and cathode is greater than zero, the resistance of an ideal diode is zero and current becomes infinite. However, if the voltage is less than zero, the resistance becomes infinite and current is zero.

Simplified Diode Model



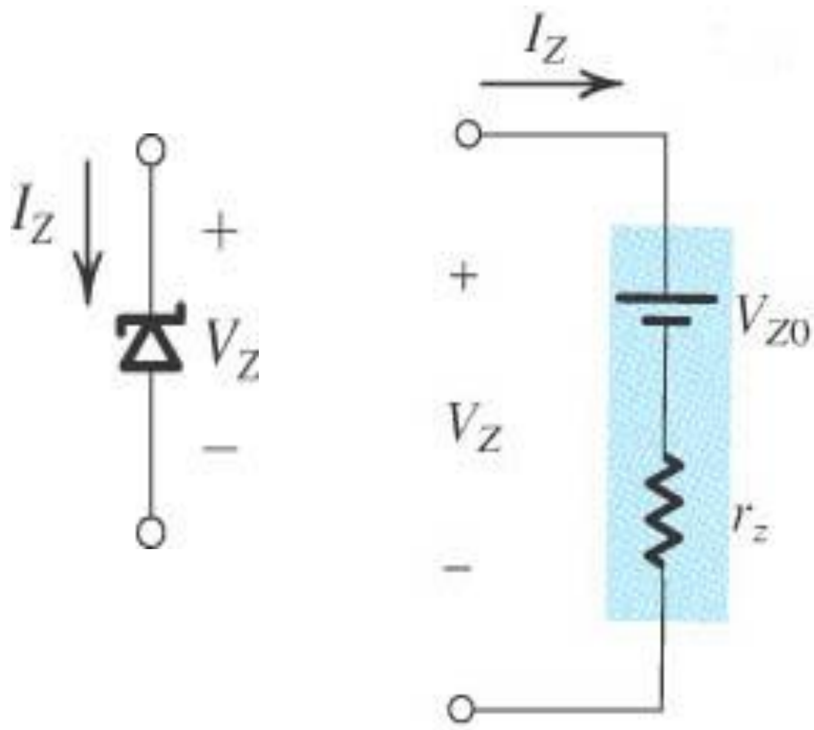
Piecewise-linear model of the diode forward characteristic and its equivalent circuit representation.

The Constant-Voltage-Drop Model



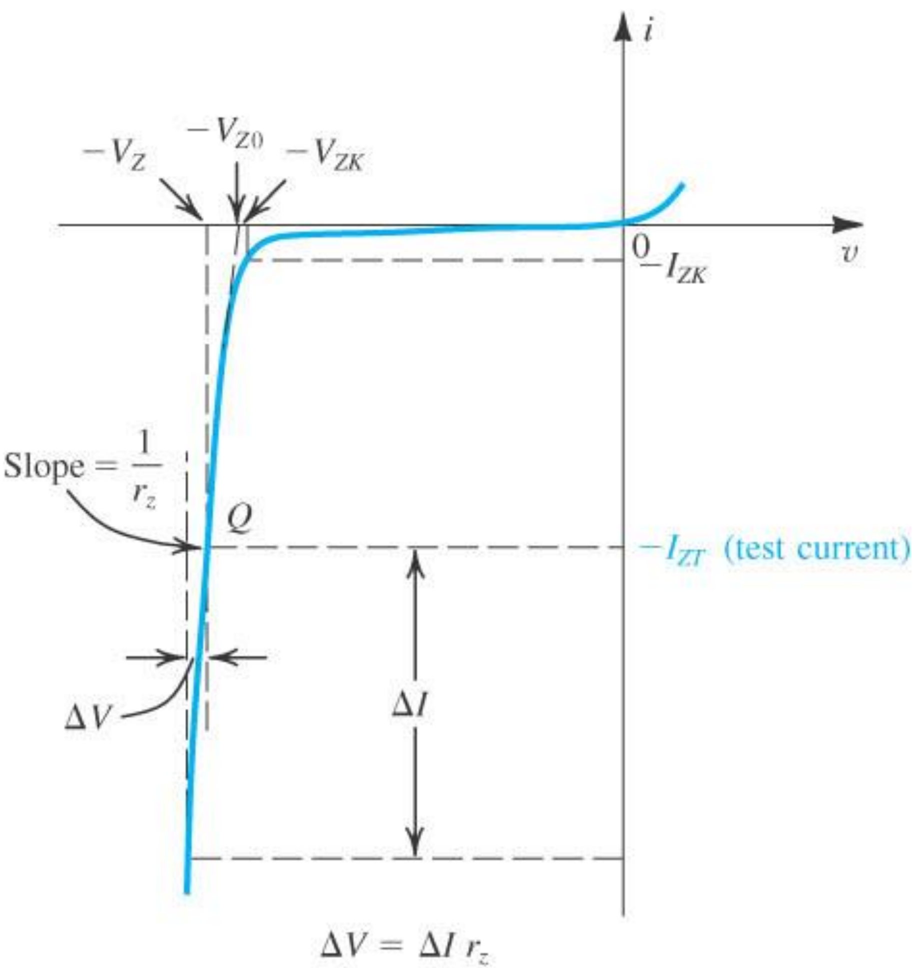
The constant-voltage-drop model of the diode forward characteristics and its equivalent-circuit representation.

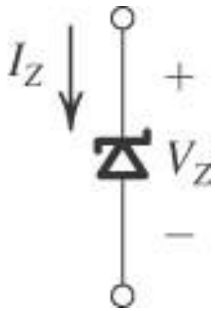
Zener Diode Model



$$V_Z = V_{Z0} + I_Z r_Z$$

Zener Diode

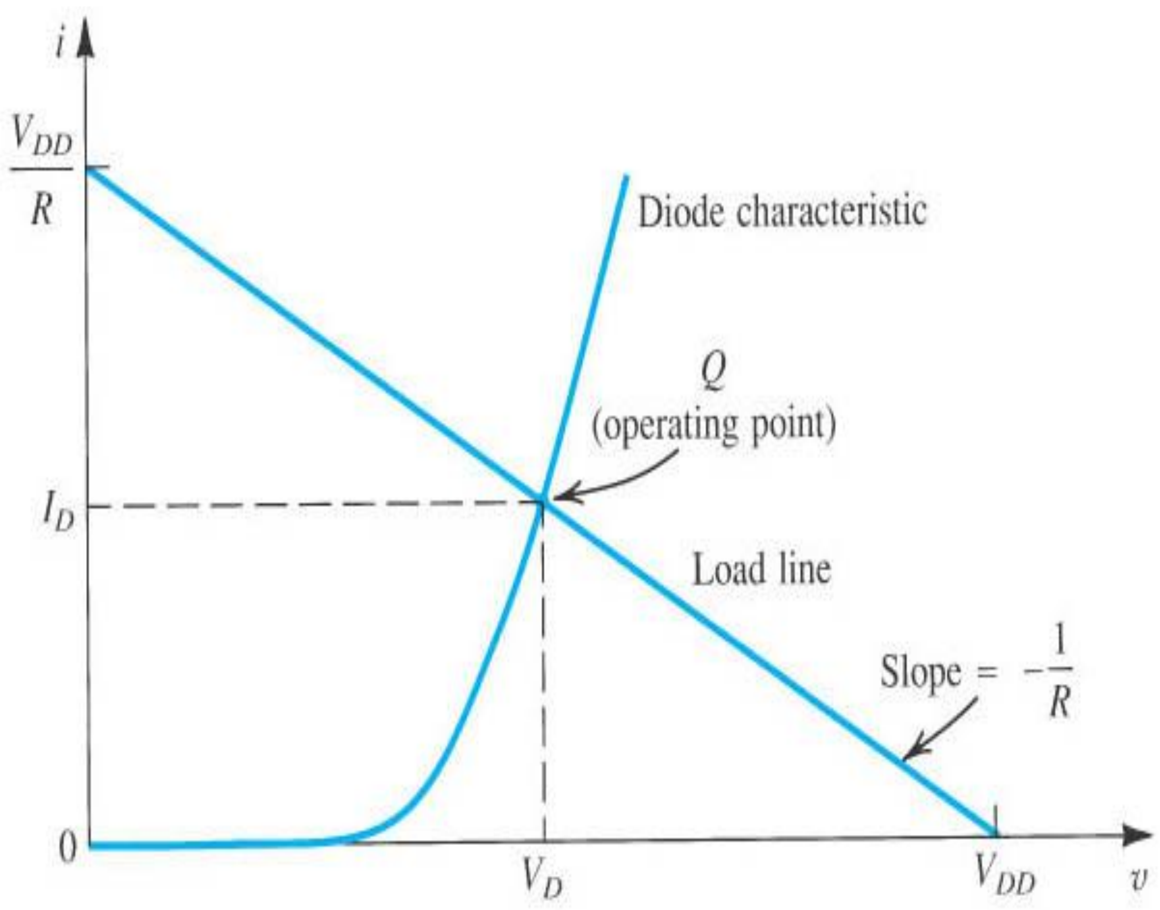




Circuit symbol

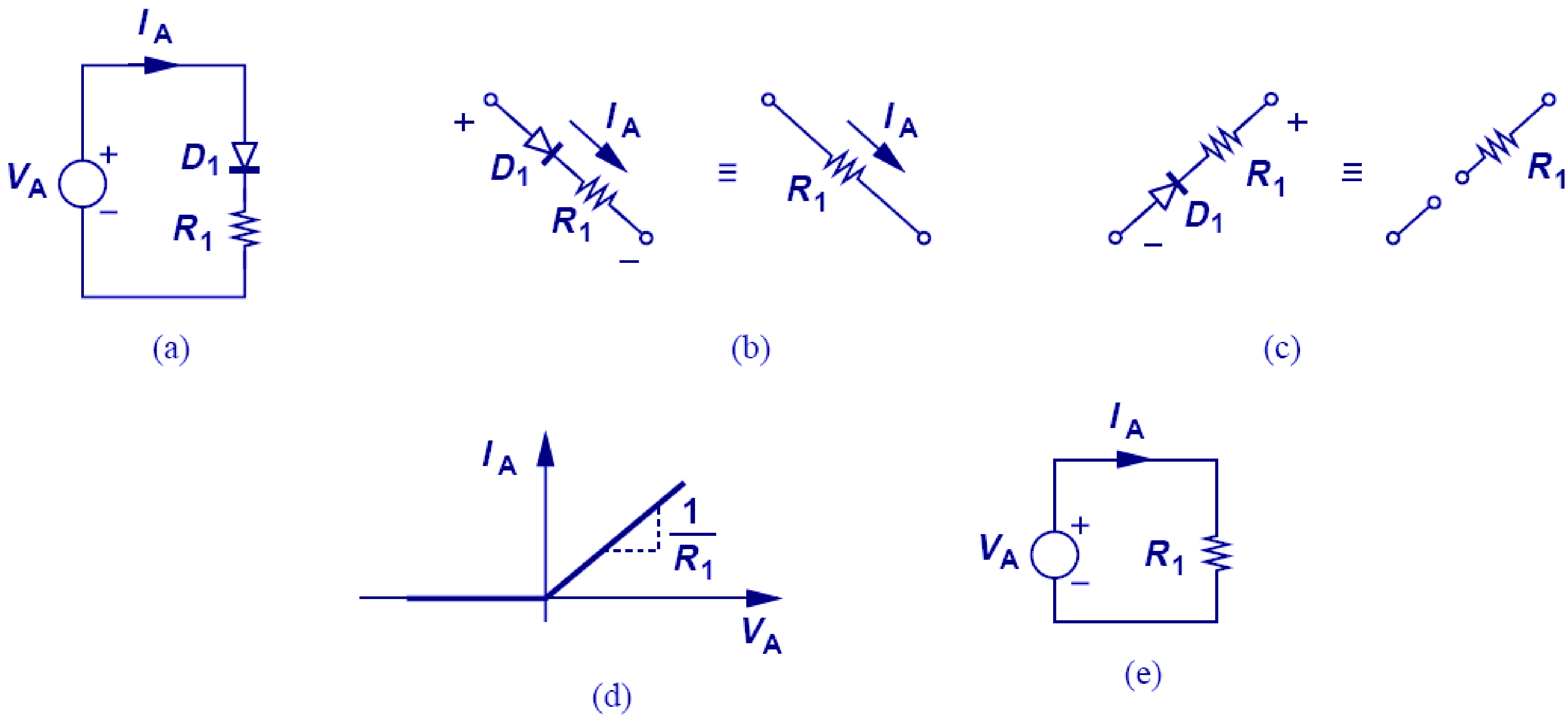
The diode *i*–*v* characteristic with the breakdown region shown in some detail.

Method of Analysis



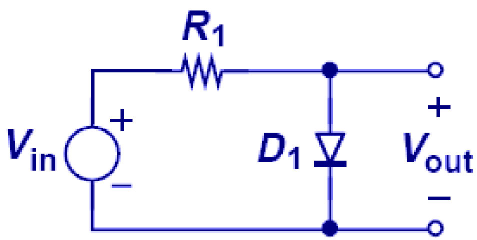
- Load line
- Diode characteristic
- Q is the intersect point
- Visualization

Diode-Resistor Combination

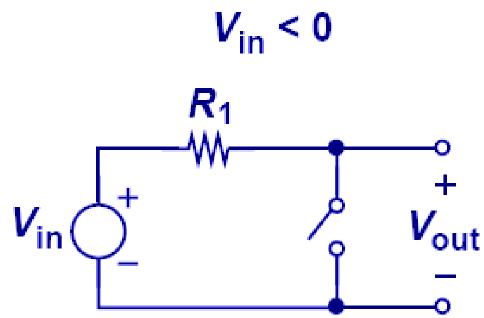


- The IV characteristic of this diode-resistor combination is zero for negative voltages and Ohm's law for positive voltages.

Input/Output Characteristics



(a)



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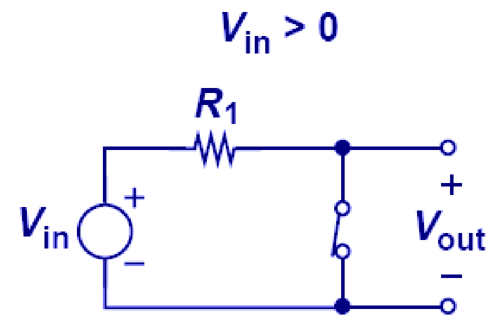

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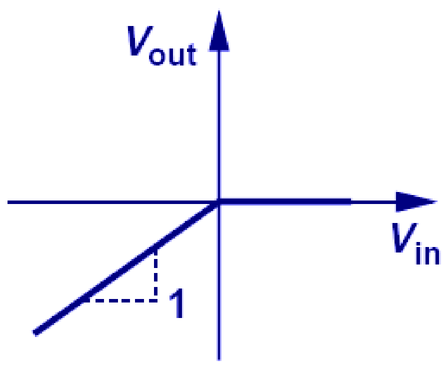
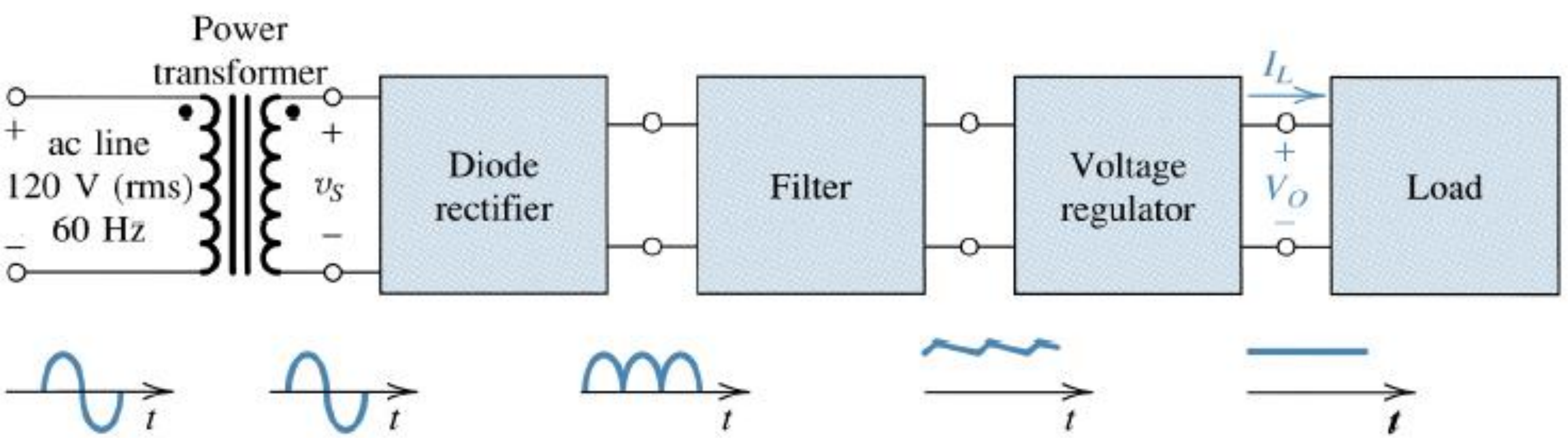


(d)

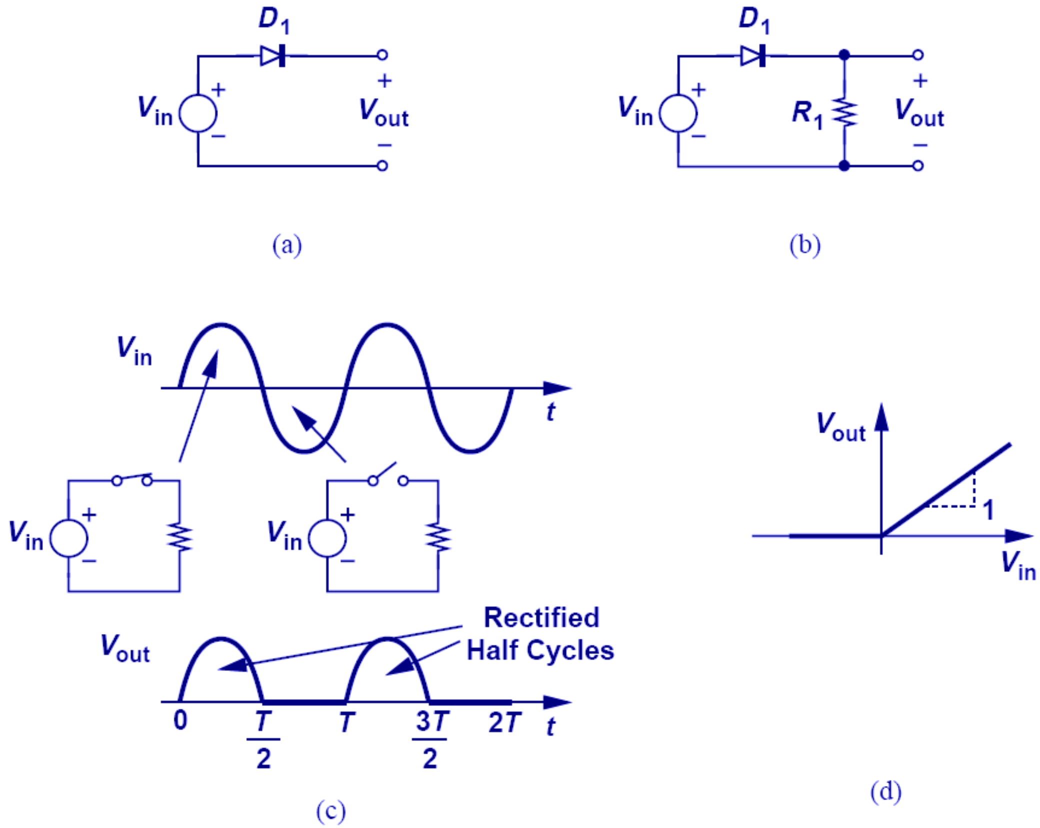
- When V_{in} is less than zero, the diode opens, so $V_{out} = V_{in}$.
- When V_{in} is greater than zero, the diode shorts, so $V_{out} = 0$.

Rectifier Circuits

One of the most important applications of diodes is in the design of rectifier circuits. Used to convert an AC signal into a DC voltage used by most electronics.

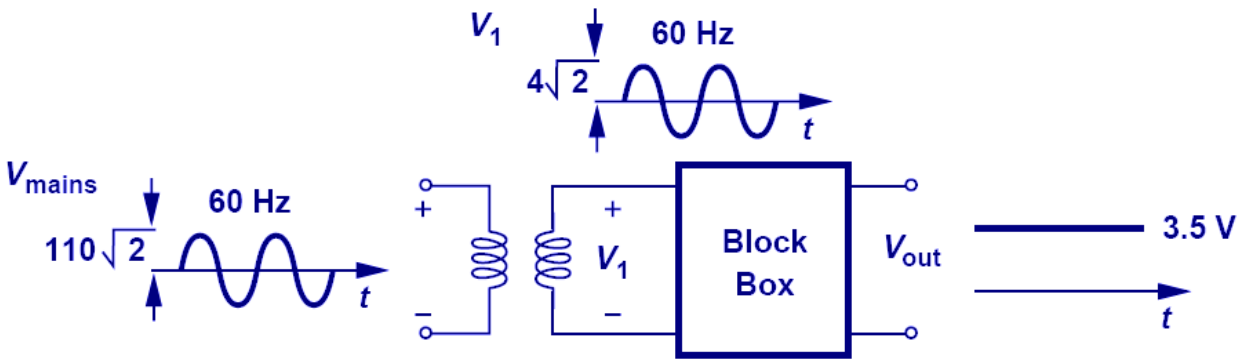


Diode's Application: Rectifier



- A rectifier is a device that passes positive-half cycle of a sinusoid and blocks the negative half-cycle or vice versa.
- When V_{in} is greater than 0, diode shorts, so $V_{out} = V_{in}$; however, when V_{in} is less than 0, diode opens, no current flows thru R_1, $Vout = I_{R1}R_1 = 0$.

Diode's Application: Cell Phone Charger



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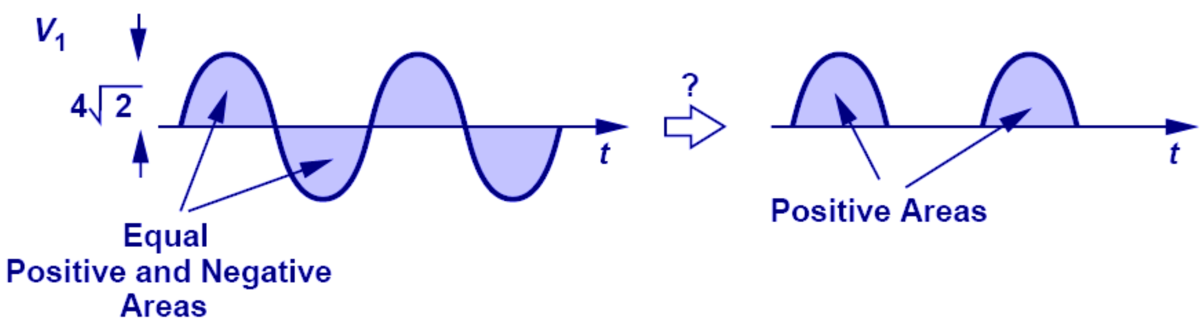
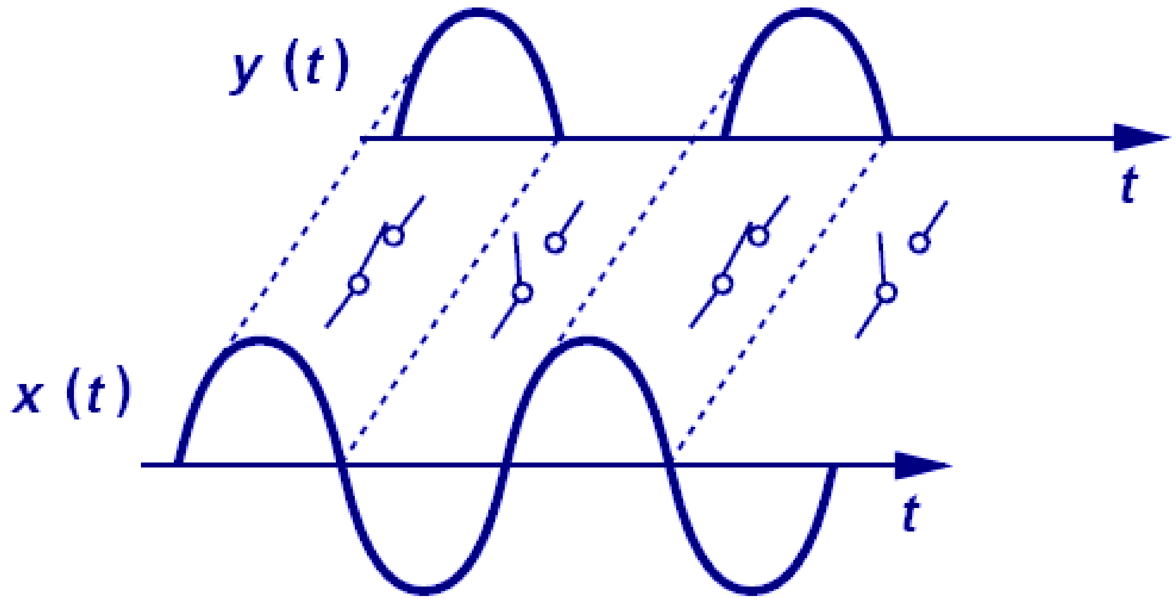


(b)

- An important application of diode is chargers.
- Diode acts as the black box (after transformer) that passes only the positive half of the stepped-down sinusoid.

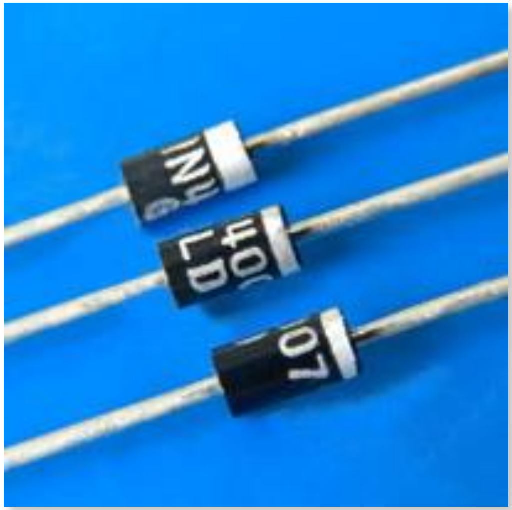
Diode's Action in The Black Box (Ideal Diode)



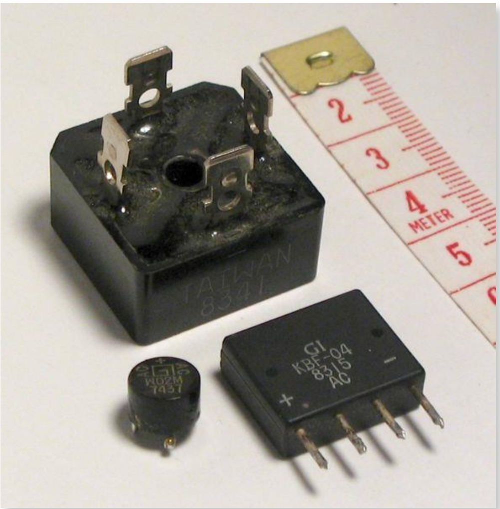
- The diode behaves as a short circuit during the positive half cycle (voltage across it tends to exceed zero), and an open circuit during the negative half cycle (voltage across it is less than zero).

Rectification Technologies

- Rectification Based on Diode
  - Rectification is most popular application of diode
  - Diodes provide compact and inexpensive means of rectification
  - Can create rectifiers from multiple diodes or purchase integrated module

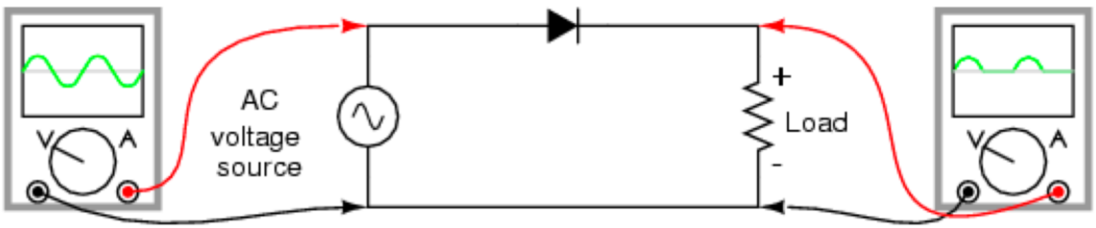


Diodes

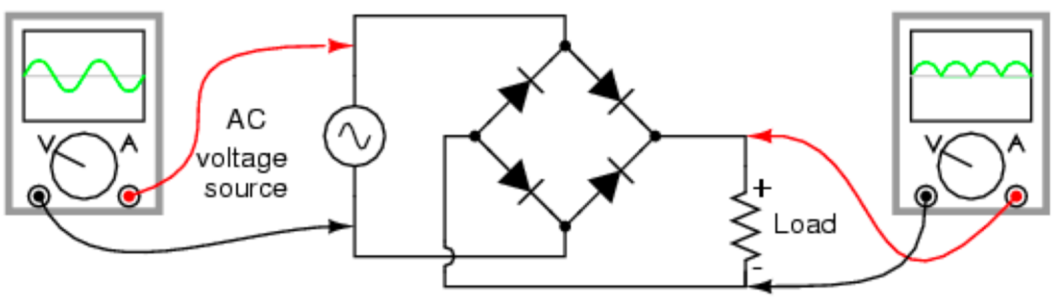


Diode Rectifier Modules

Types of Rectification



Half Wave Rectifier

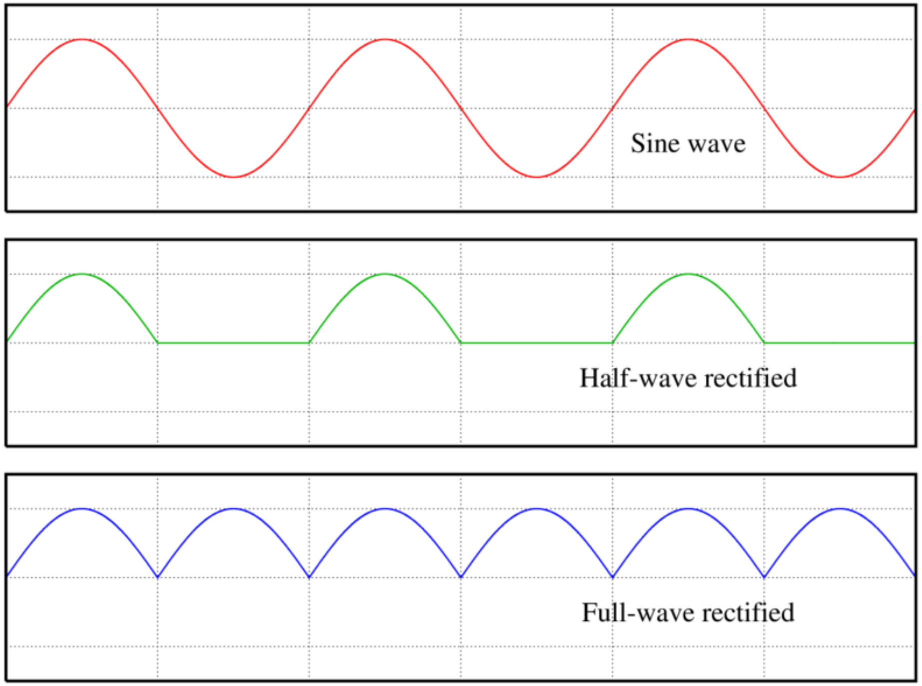


Full Wave Rectifier

- While output of the rectifiers is now DC (current only flows in one direction), output oscillates

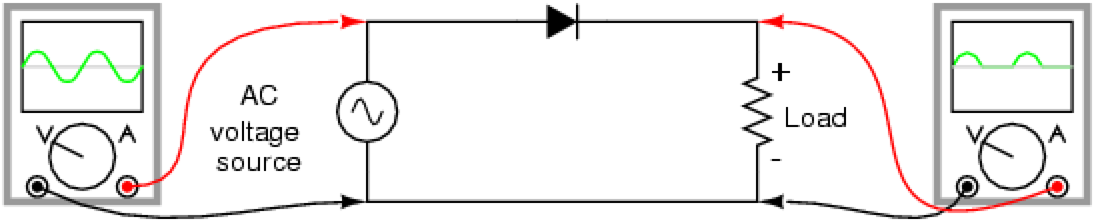
Types of Rectification

- Half Wave:
  - Negative components of sine wave are discarded
- Full Wave:
  - Negative components are inverted



Rectification Circuit: Half-Wave

- Simplest kind of rectifier circuit is *half-wave* rectifier.
- Allows one half of AC waveform to pass through to load.
- Converts alternating current (AC) to direct current (DC).
- Involves device that only allows one-way flow of electrons, and this is exactly what semiconductor diode does.



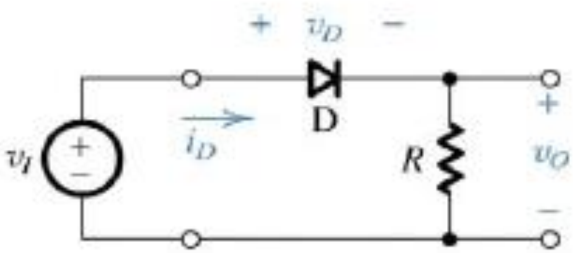
Half-wave rectifier circuit

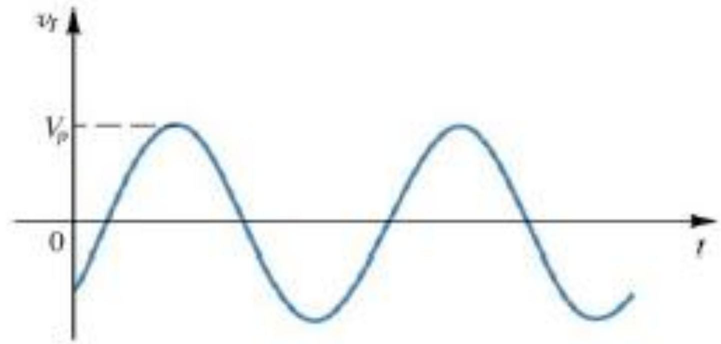
Half-Wave Rectifier

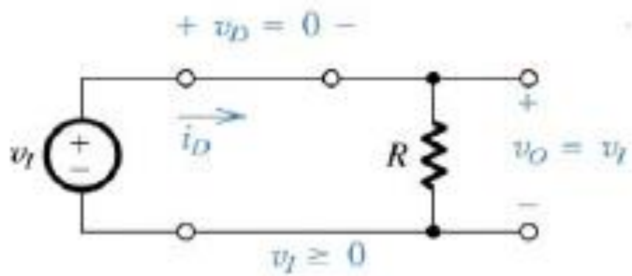
(a) Half-wave rectifier.

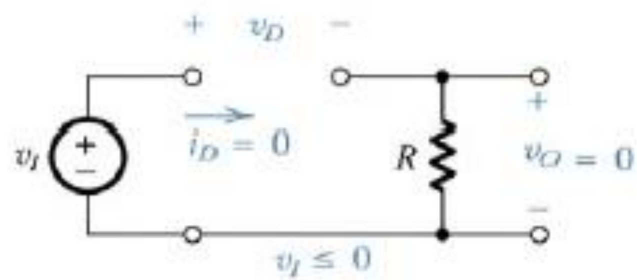
(b) Equivalent circuit of the half-wave rectifier with the diode replaced with its battery-plus-resistance model.

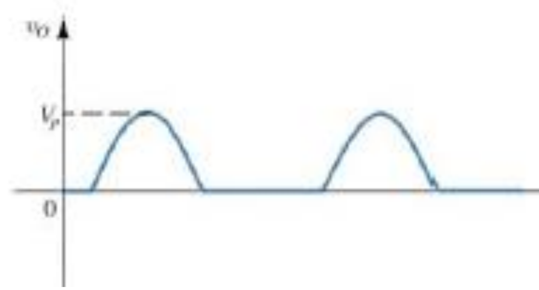
Simple Half-Wave Rectifier



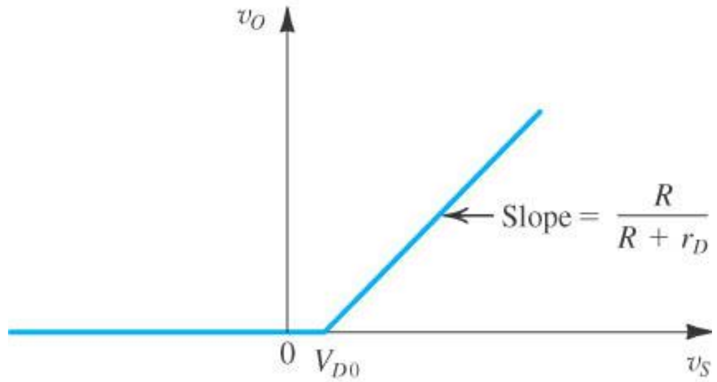


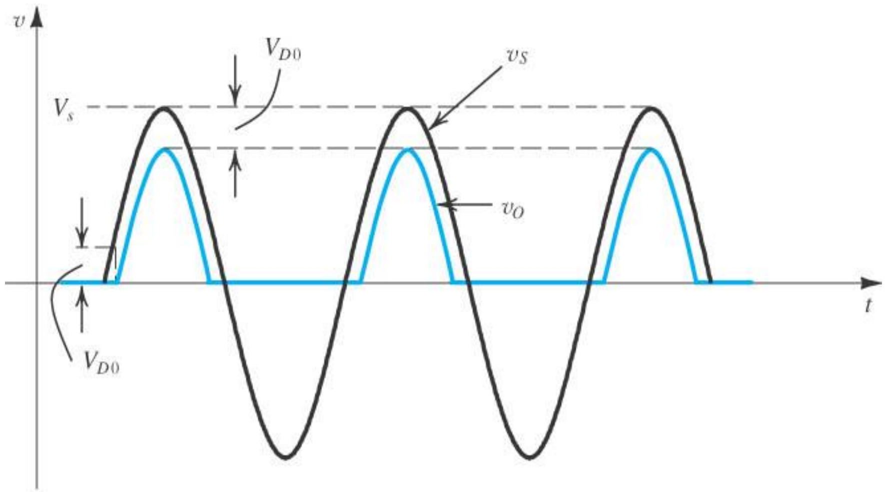






What would the waveform look like if not an ideal diode?

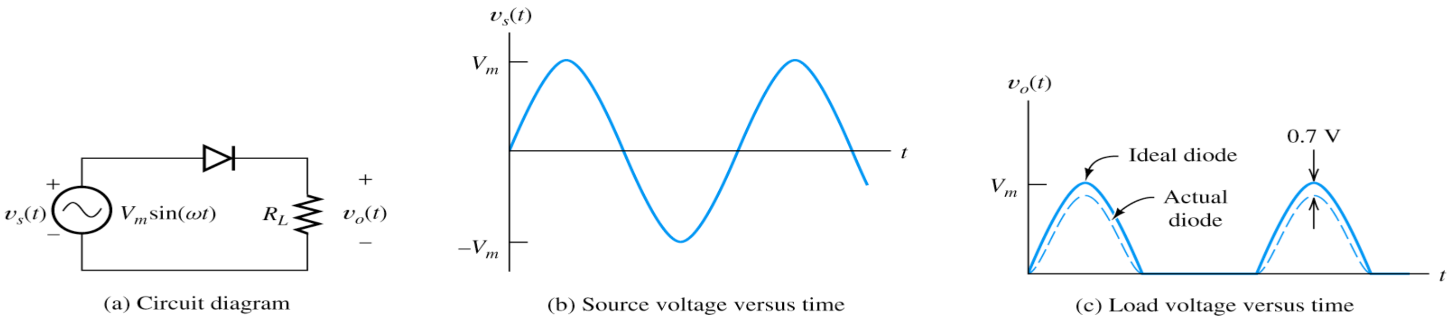




(c) Transfer characteristic of the rectifier circuit.

(d) Input and output waveforms, assuming that $r_D \ll R$

* *Half-Wave Rectifier with Smoothing Capacitor*



* To place a large capacitance across the output terminals:

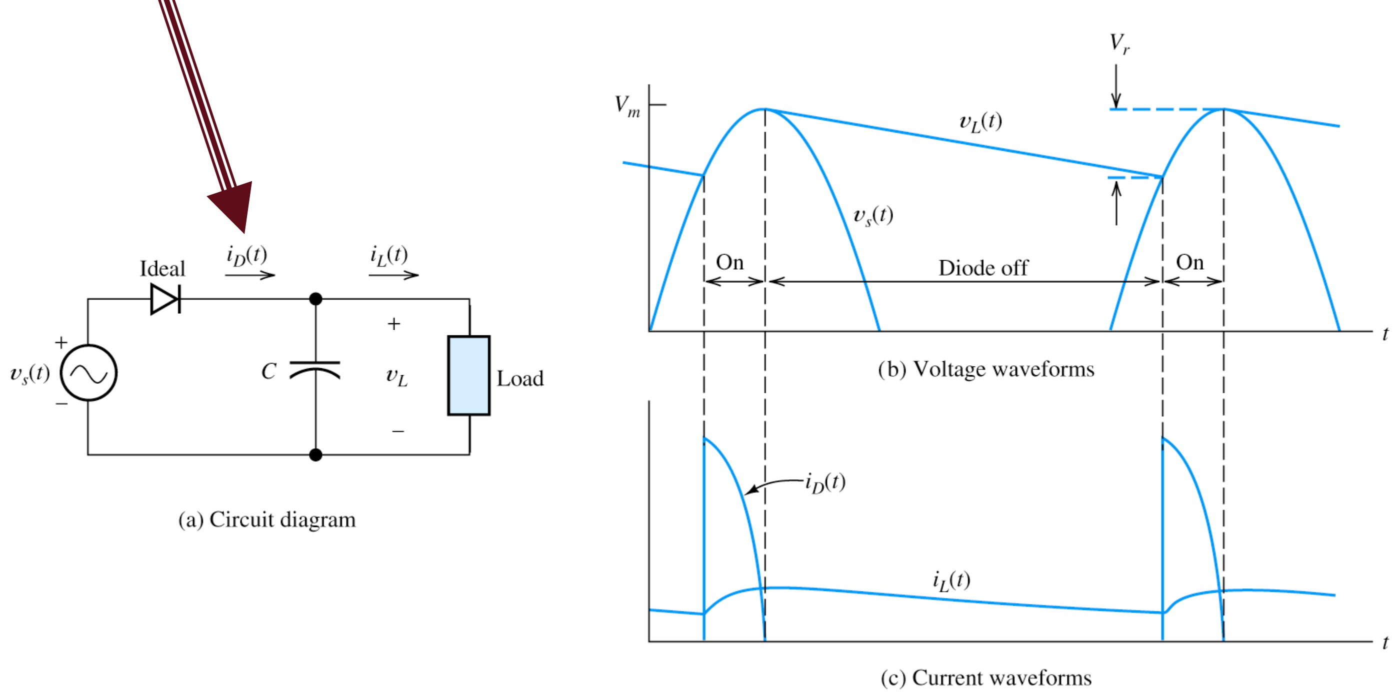


Figure 10.26 Half-wave rectifier with smoothing capacitor.

* *Battery-Charging Circuit*

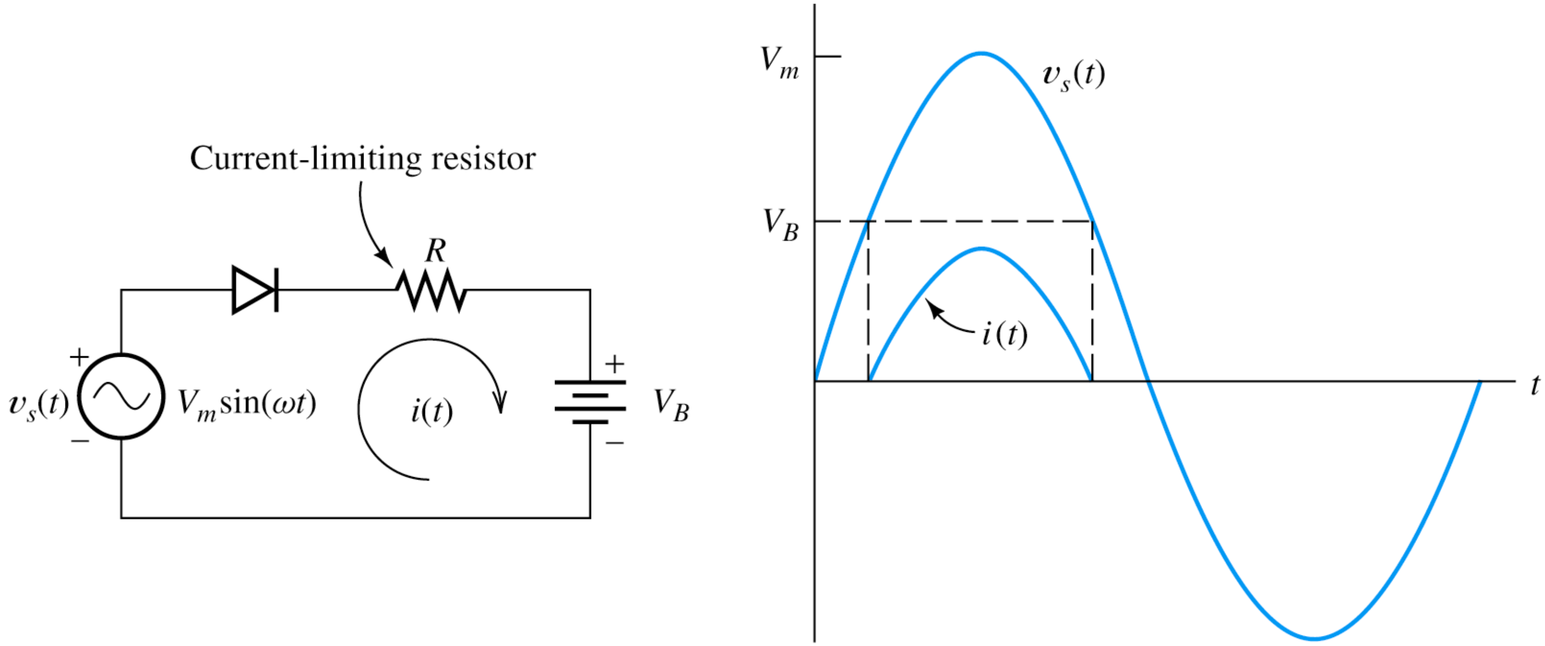


Figure 10.25 Half-wave rectifier used to charge a battery.

* The current flows only in the direction that charges the battery.

Average or DC Value

$$V_{out} = V_p \sin \omega t = 0 \qquad for \qquad 0 \le t \le \frac{T}{2}$$

$$V_{out,avg} = \frac{1}{T}\int_0^T V_{out}(t)dt = \frac{1}{T}\int_0^{T/2} V_p \sin \omega t dt$$

$$= \frac{1}{T}\frac{V_p}{\omega}\left[-\cos \omega t\right]_0^{T/2} = \frac{V_p}{\pi} \qquad for \quad \frac{T}{2} \le t \le T$$

- The averaged value of a rectifier output can be used as a signal strength indicator for the input, since $V_{out,avg}$ is proportional to V_p, the input signal's amplitude.

$$V_p = V_m \qquad I_p = I_m$$

$$I_{avg} = I_{dc} = \frac{V_{dc}}{R_L}$$

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

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

$$V_{dc} = \frac{V_m}{\pi} - I_{dc}.R_f$$

$$I_{dc} = \frac{V_m}{\pi(R_L + R_f)}$$

R_f = forward resistance of Diode
R_L = Load Resistance
V_p /V_m = Peak Voltage
I_p /I_m = Peak Current
I_{dc}/I_{avg} = Load Current
V_{dc} = output dc Voltage

The rms value of the current, I_{rms} can be derived as:

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_m{}^2 \sin^2 \omega t d(\omega t)}$$

$$I_{rms} = \sqrt{\frac{I_m{}^2}{2\pi}\int_0^{\pi} \frac{1}{2}(1-\cos 2\omega t)d(\omega t)}$$

$$I_{rms} = \sqrt{\frac{I_m{}^2}{2\pi} \times \frac{1}{2}\left[\omega t + \frac{1}{2}\sin 2\omega t\right]_0^{\pi}}$$

$$I_{rms} = \sqrt{\frac{I_m{}^2}{4\pi} \times [\pi]}$$

$$I_{rms} = \frac{I_m}{2} = 0.5 I_m$$

The voltage across the load is given by:

$$V_R = Ri = R I_m \sin \omega t = V_m \sin \omega t$$

Similarly, the mean value of the load voltage and the rms value of the effective input voltage are respectively given by:

$$V_{dc} = \frac{V_m}{\pi} = 0.318 V_m$$

$$V_{rms} = \frac{V_m}{2} = 0.5 V_m$$

Efficiency of a half-wave rectifier

$$\text{Rectifier efficiency, } \eta = \frac{\text{output dc power}}{\text{input ac power}}$$

$$\eta = \frac{I_{dc}^{\ 2} R}{I_{rms}^{\ 2}(r_f + R)}$$

$$\eta = \frac{\left[\frac{I_m}{\pi}\right]^2 R}{\left[\frac{I_m}{2}\right]^2 (r_f + R)}$$

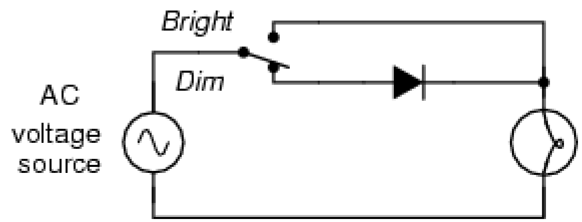
$$\eta = \frac{4}{\pi^2}\left[\frac{R}{(r_f + R)}\right]$$

$$\eta = \frac{0.405}{1 + \frac{r_f}{R}}$$

For maximum efficiency, the value of r_f should be negligible compared to R. Therefore, the maximum efficiency of the half-wave rectifier is 40.5%.

Rectification Circuit: Half-Wave

- For most power applications, half-wave rectification is insufficient for task.
  - Harmonic content of rectifier's output waveform is very large and consequently difficult to filter.
  - AC power source only supplies power to load once every half-cycle, meaning that much of its capacity is unused.
  - Half-wave rectification is, however, very simple way to reduce power to resistive load.
- Two-position lamp dimmer switches apply full AC power to lamp filament for "full" brightness and then half-wave rectify it for a lesser light output.



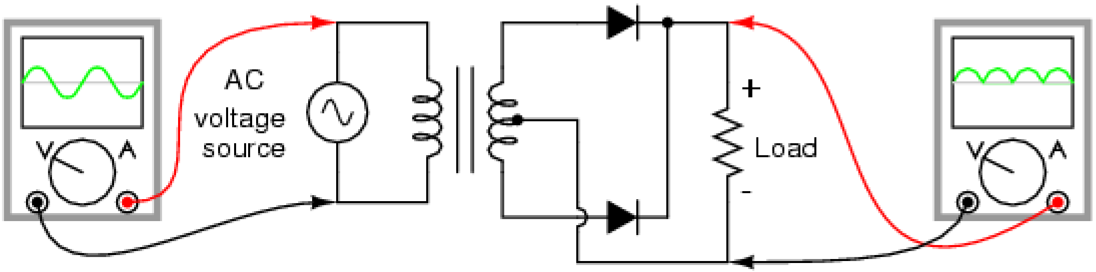
Half-wave rectifier application: Two level lamp dimmer.

Rectification Circuit: Half-Wave

- In “Dim” switch position, incandescent lamp receives approximately one-half power it would normally receive operating on full-wave AC.
  - Because half-wave rectified power pulses far more rapidly than filament has time to heat up and cool down, lamp does not blink.
  - Instead, its filament merely operates at lesser temperature than normal, providing less light output.
- This principle of “pulsing” power rapidly to slow-responding load device to control electrical power sent to it is common in world of industrial electronics.
- Since controlling device (diode, in this case) is either fully conducting or fully non-conducting at any given time, it dissipates little heat energy while controlling load power, making this method of power control very energy-efficient.
- This circuit is perhaps crudest possible method of pulsing power to a load, but it suffices as a proof-of-concept application.

Rectifier Circuit: Full-Wave

- If we need to rectify AC power:
  - In order obtain full use of *both* half-cycles of sine wave
    - *Full-wave* rectifier must be used
- Types of full-wave rectifier:
  - Center-tap design
  - Full-wave bridge.
- *Center-tap* design
    - Uses transformer with center-tapped secondary winding and two diodes



Full-wave rectifier, center-tapped design.

Full-Wave Rectifier Circuits

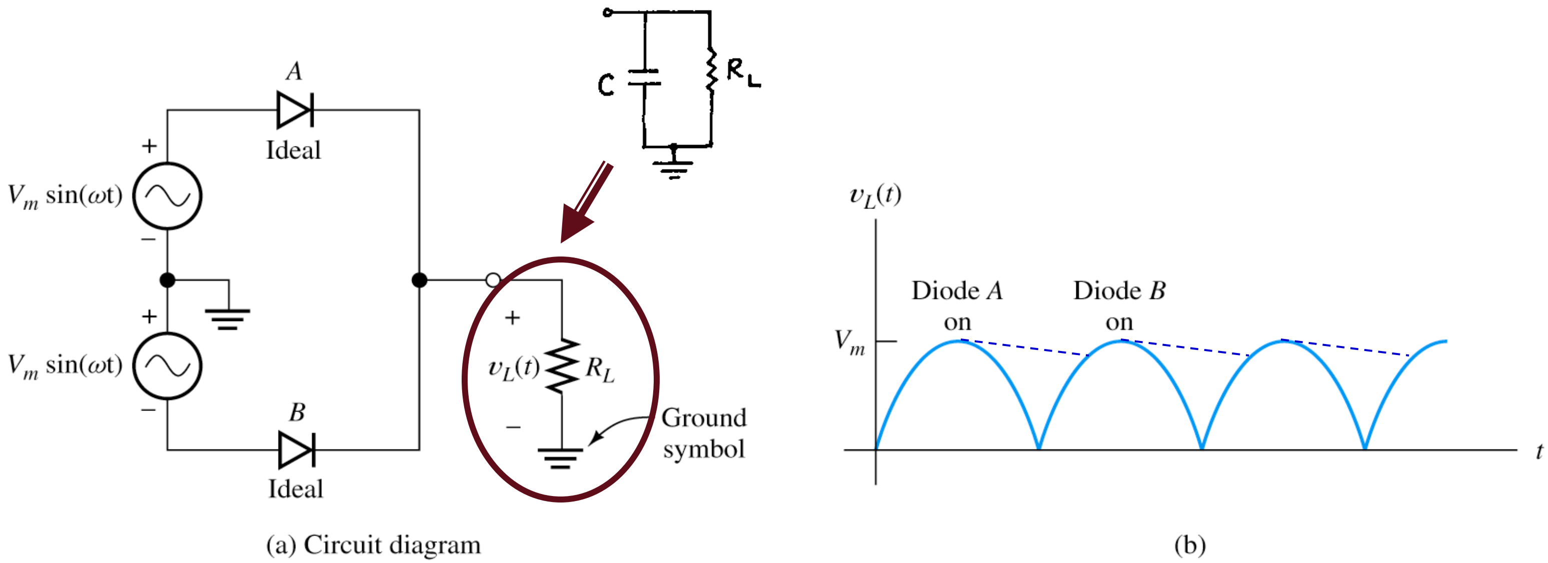


Figure 10.27 Full-wave rectifier.

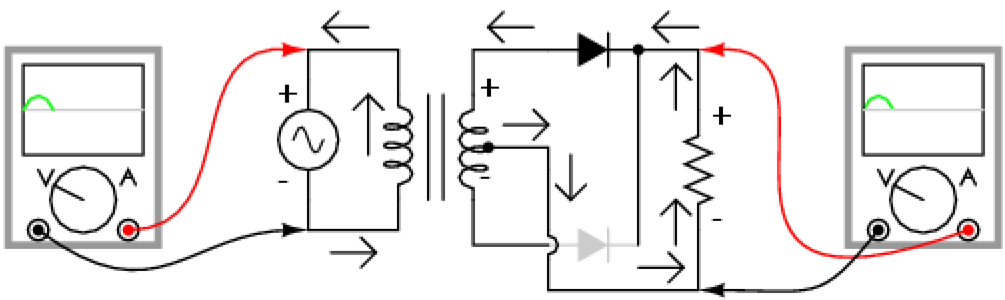
* *Centre-Tapped Full-Wave Rectifier* – two half-wave rectifier with out-of-phase source voltages and a common ground.

* When upper source supplies "+" voltage to diode A, the lower source supplies "-" voltage to diode B; and vice versa.

* We can also smooth the output by using a large capacitance.

Rectifier circuit

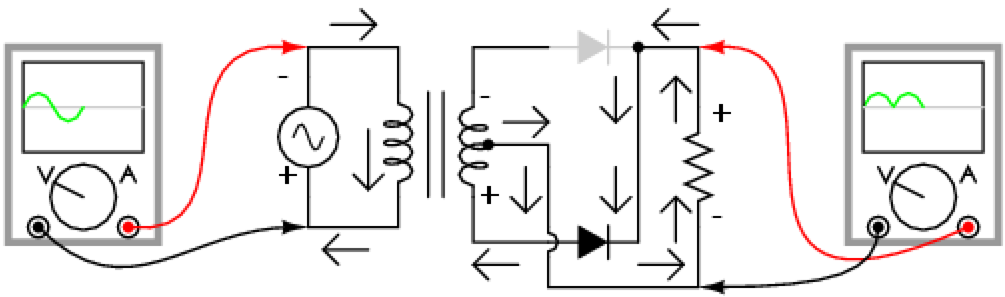
- Look at its circuit operation one half-cycle at a time.
- **Consider first half-cycle:**
  - Source voltage polarity is positive (+) on top and negative (-) on bottom.
  - Only top diode is conducting; bottom diode is blocking current, and load "sees" first half of sine wave.
  - Only top half of transformer's secondary winding carries current during this half-cycle.



Full-wave center-tap rectifier: Top half of secondary winding conducts during positive half-cycle of input, delivering positive half-cycle to load.

Rectifier circuit

- Consider next (second) half-cycle:
  - AC polarity reverses
  - Other diode and other half of transformer's secondary winding now carry current
  - Portions of circuit formerly carrying current during first half-cycle sit idle
  - Load still “sees” half of sine wave, of same polarity as before.



Full-wave center-tap rectifier: During negative input half-cycle, bottom half of secondary winding conducts, delivering a positive half-cycle to the load.

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

$$V_m = \frac{V_{p(sec)}}{2}$$

$$\Rightarrow V_{p(sec)} = 2V_m$$

$$PIV = V_{p(sec)} = 2V_m$$

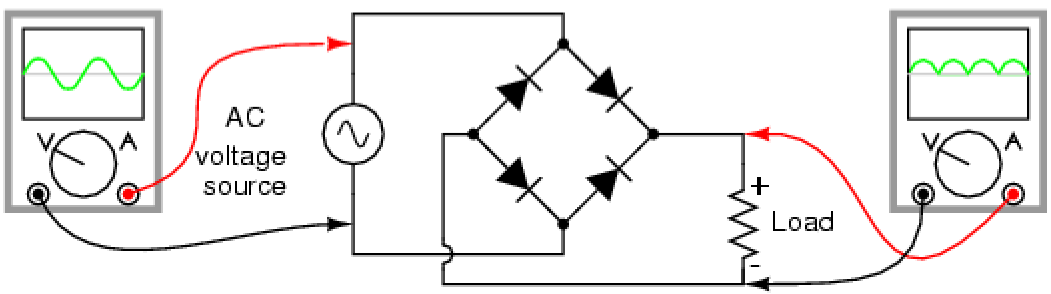
Rectifier Circuit: Full-Wave

- One disadvantage of this full-wave rectifier design is:
  - Necessity of transformer with center-tapped secondary winding.
- If circuit in question is one of high power:
  - Size and expense of suitable transformer will be significant.
- Consequently:
  - Center-tap rectifier design is only seen in low-power applications.

Disadvantages

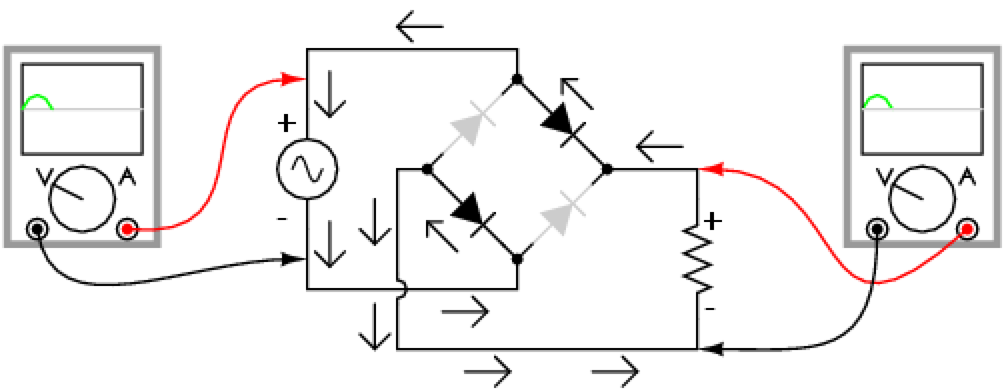
1. Since, each diode uses only one-half of the transformers secondary voltage, the d.c. output is comparatively small.
2. It is difficult to locate the centre-tap on secondary winding of the transformer.
3. The diodes used must have high peak-inverse voltage.

- **Full-wave Bridge Rectifier.**
  - More popular full-wave rectifier design
  - Built around four-diode bridge configuration.
  - For obvious reasons, this design is called *full-wave bridge*.



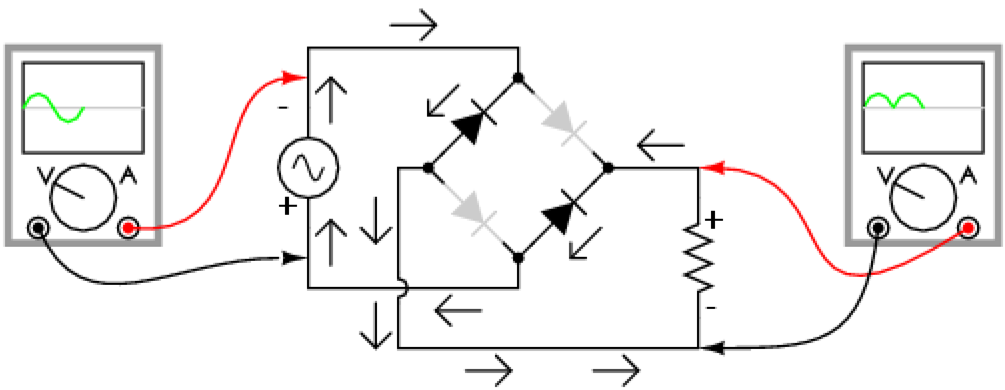
Full-wave bridge rectifier.

- **Full-wave Bridge**
  - Current directions for positive and negative half-cycles of:
    - AC source waveform are shown below and next page respectively.
  - Note: regardless of polarity of input, current flows in same direction through load.
  - That is, negative half-cycle of source is positive half-cycle at load.



Full-wave bridge rectifier: Electron flow for positive half-cycles

Rectifier circuit: Full-Wave Bridge

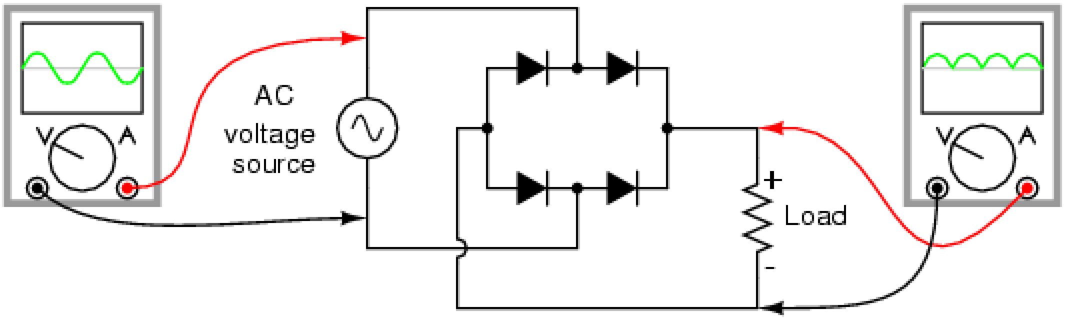


Full-wave bridge rectifier: Electron flow for negative half -cycles.

- Current flow is through two diodes in series for both polarities.
- Thus, sum of voltage drops for two diodes is 2(0.7) volts
- This is disadvantage when compared to full-wave center-tap design.
  - Will only be problem in very low voltage power supplies

Full-wave Bridge: with horizontal altitude

- Remembering proper layout of diodes in full-wave bridge rectifier circuit can often be frustrating some times.
- Alternative representation of this circuit is easier both to remember and to comprehend.
- It is exact same circuit, except all diodes are drawn in horizontal altitude, all “pointing” same direction.



Alternative layout style for Full-wave bridge rectifier.

- One advantage of remembering this layout for bridge rectifier circuit is that it expands easily into poly-phase version (beyond basic electronics).

Disadvantages

- It requires four diodes.
- The use of two extra diodes cause an additional voltage drop thereby reducing the output voltage.

Efficiency of a full-wave rectifier

$$\text{Rectifier efficiency, } \eta = \frac{\text{output dc power}}{\text{input ac power}}$$

$$\eta = \frac{I_{dc}{}^2 R}{I_{rms}{}^2 (2r_f + R)}$$

$$\eta = \frac{\left[\frac{2I_m}{\pi}\right]^2 R}{\left[\frac{I_m}{\sqrt{2}}\right]^2 (2r_f + R)}$$

$$\eta = \frac{8}{\pi^2}\left[\frac{R}{(r_f + R)}\right]$$

$$\eta = \frac{0.81}{1 + \frac{2r_f}{R}}$$

For a bridge rectification circuit, the supply passes through two diodes ($2\ r_f$) at any particular time

In the case of a centre-tap rectification circuit, only one diode conducts at any particular time.
Thus, its efficiency will be

$$\eta = \frac{0.81}{1 + \frac{r_f}{R}}$$

For maximum efficiency, the value of r_f should be negligible compared to R. Therefore, the maximum efficiency of the full-wave rectifier is 81% and is twice as efficient as the half-wave rectifier.

The **peak inverse voltage (PIV)** of the diode is the peak value of the voltage that a diode can withstand when it is reversed biased

Type of Rectifier	PIV
Half Wave	Peak value of the input secondary voltage, $V_{m\ (peak)}$
Full Wave : Center-Tapped	$2V_{m(peak)}$
Full Wave: Bridge	$V_{m(peak)}$

Rectifier circuit

- In any case of rectification: single-phase or poly-phase
    - **Amount of AC voltage mixed with rectifier's DC output** is called *ripple voltage*.
- In most cases, since "pure" DC is desired goal
    - Ripple voltage is undesirable.
- If power levels are not too great
    - Filtering networks may be employed to reduce amount of ripple in output voltage.

Output Ripple

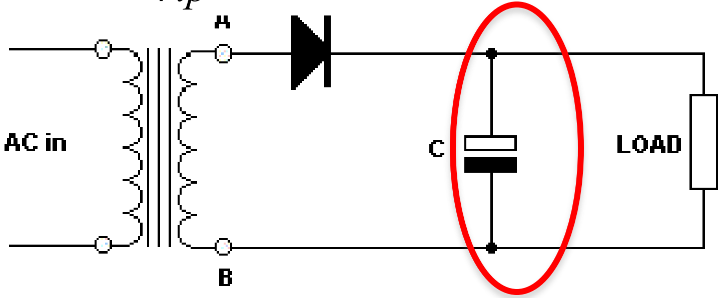
- Output ripple will always be present in circuits shown above
- Amplitude of ripple can be reduced by adding smoothing capacitor
- Capacitor and load (shown here as resistor) from low pass filter with time constant : T = RC
- Time constant should be much longer than one ripple
- For given ripple amplitude: capacitor size (in microfarads) is given by

$$C = \frac{I_{load}}{fV_{rip}} \times 10^6 \;\; (Half \;\; wave) \quad or \quad C = \frac{I_{load}}{2fV_{rip}} \times 10^6 \;\; (Full \;\; wave)$$

f: line frequency

I_{load}: Load Current

V_{rip}: Amplitude of ripple voltage



NOTE: Voltage rating of the capacitor must be > 1.4*V_{out}

Large capacitors should have bleeder resistors for safety!

Rectifier Circuit: Output Voltage

- Full wave rectification will produce voltage roughly equal to

$$V_o \approx \sqrt{2} V_{i,RMS}$$

- In practice, there will be small voltage drop across diodes that will reduce this voltage
- For accurate supplies, regulation is necessary

Rectifier circuit

REVIEW:

- *Rectification* is conversion of alternating current (AC) to direct current (DC).
- A *half-wave* rectifier is circuit that allows only one half-cycle of AC voltage waveform to be applied to load, resulting in one non-alternating polarity across it.
  - The resulting DC delivered to load “pulsates” significantly.
- A *full-wave* rectifier is circuit that converts both half-cycles of AC voltage waveform to unbroken series of voltage pulses of same polarity.
  - The resulting DC delivered to load doesn't “pulsate” as much.

- The *ripple factor* indicates how close the rectified output is to the pure ideal dc voltage waveform
- The rms value of a full-wave signal is $V_{rms} = 0.707V_p$, which is the same as V_{rms} for a full-wave sine wave
- *Efficiency* of a rectifier is defined as the ratio of dc power delivered to the load to the ac power from the secondary winding of the transformer

…that’s all folks…
…thanks for your time…