Diode Applications: Rectifiers and Power Supplies

Maxx Seminario

University of Nebraska-Lincoln

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Diode Applications Overview

Why Study Rectifiers?:

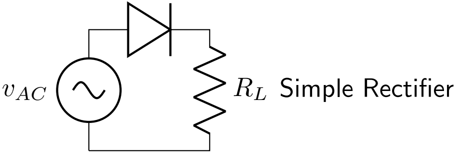
- Most electronics need DC power
- Wall outlets provide AC power
- Rectifiers convert AC to DC
- Foundation of power supplies

Key Applications:

- Battery chargers
- Computer power supplies
- LED drivers
- Motor controllers

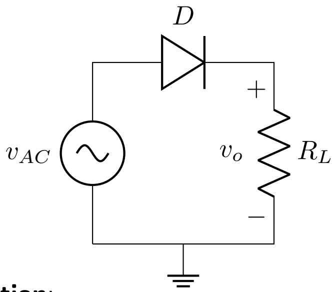
Topics We'll Cover:

- Half-wave rectifiers
- Full-wave rectifiers
- Bridge rectifiers
- Filtering capacitors
- Ripple voltage
- Voltage regulation with Zeners



Half-Wave Rectifier Circuit

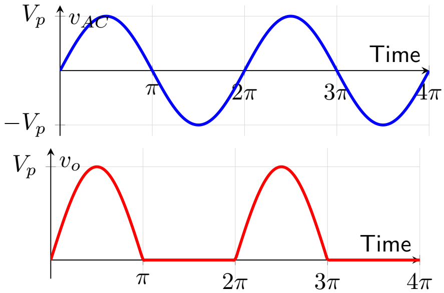
Basic Circuit:



Operation:

- Input: $v_{AC} = V_p \sin(\omega t)$
- Positive half-cycle: diode ON
- Negative half-cycle: diode OFF
- Output: positive half-waves only

Waveforms:



Half-Wave Rectifier Analysis

Average (DC) Output Voltage:
For ideal diode ($V_D = 0$):

$$V_{DC} = \frac{V_p}{\pi} \approx 0.318 V_p$$

For real silicon diode ($V_D \approx 0.7$ V):

$$V_{DC} = \frac{V_p - V_D}{\pi}$$

Peak Inverse Voltage (PIV):

- Maximum reverse voltage on diode
- Must select diode with PIV $> V_p$
- Else, diode may break down during negative half-cycle

Example Calculation:
Given: $V_{AC,RMS} = 12$ V

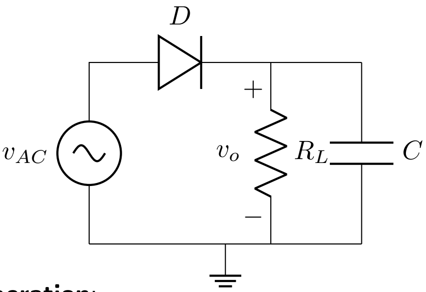
1. Peak voltage:
   $V_p = \sqrt{2} \times V_{RMS} = 17$ V
2. Calculate DC output:
   $V_{DC} = \frac{17-0.7}{\pi} = \frac{16.27}{\pi} = 5.18$ V
3. PIV requirement:
   PIV ≥ 17 V

Limitations:

- ☹ Low DC output (only 31.8%)
- ☹ Poor power utilization
- ☹ Large ripple voltage

Half-Wave Rectifier with Filter Capacitor

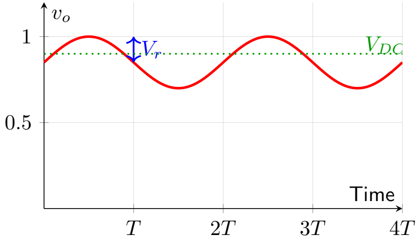
Filtered Rectifier:



Operation:

- Capacitor charges to $\approx V_p$
- Capacitor discharges through R_L
- Creates "ripple" voltage
- DC voltage higher than unfiltered

Output Waveform:



Ripple Voltage:

$$V_r \approx \frac{V_p}{f R_L C}$$

Ripple Voltage Analysis

Key Equations:

Ripple voltage (peak-to-peak):

$$V_r \approx \frac{V_p}{fR_LC}$$

DC output voltage:

$$V_{DC} \approx V_p - \frac{V_r}{2}$$

Ripple factor:

$$r = \frac{V_{r,RMS}}{V_{DC}}$$

Design Guidelines:

- ☺ Larger C reduces ripple
- ☺ Larger R_L reduces ripple
- ☺ Higher frequency reduces ripple

Example:

Given:

- $V_p = 17$ V
- $f = 60$ Hz
- $R_L = 2.2$ kΩ
- $C = 470$ μF

Calculate ripple:

$$V_r = \frac{17}{60 \times 2200 \times 470 \times 10^{-6}} = 0.274 \text{ V}$$

$$V_{DC} = 17 - \frac{0.274}{2} = 16.86 \text{ V}$$

Trade-offs:

- Large C: less ripple, larger size
- Peak diode current increases with C

Bridge Rectifier Circuit

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Introduction

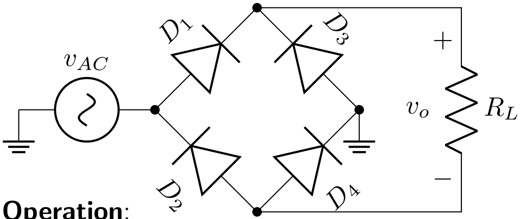
Half-Wave Rectifiers

Full-Wave Rectifiers

Voltage Regulation

Summary

Bridge Configuration:



Operation:

- Positive half-cycle: D_1, D_4 conduct
- Negative half-cycle: D_2, D_3 conduct
- Both half-cycles produce output
- Two diodes always in series

Output Characteristics:

- v_o is always positive
- Output is full-wave rectified
- Continuous current through load

Advantages:

- ☺ No center-tap transformer needed
- ☺ Full-wave rectification
- ☺ Higher DC output
- ☺ Lower ripple frequency ($2f$)

Disadvantages:

- ☹ Two diode drops (≈ 1.4 V)
- ☹ Requires four diodes

Bridge Rectifier Analysis

DC Output Voltage:
For ideal diodes ($V_D = 0$):

$$V_{DC} = \frac{2V_p}{\pi} \approx 0.637V_p$$

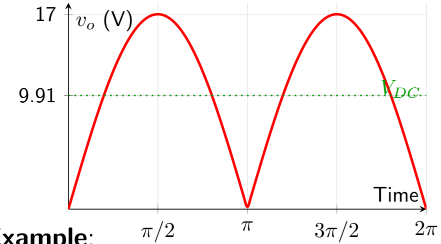
For real silicon diodes ($V_D \approx 0.7$ V each):

$$V_{DC} = \frac{2(V_p - 2V_D)}{\pi}$$

Comparison to Half-Wave:

- DC output is 2x higher
- Ripple frequency is 2x higher
- Better power utilization

Output Waveform:



Example:
$V_{AC,RMS} = 12$ V, $V_p = 17$ V

$$V_{DC} = \frac{2(17 - 1.4)}{\pi} = \frac{31.14}{\pi} = 9.91 \text{ V}$$

Compare to half-wave: 5.18 V (nearly 2x improvement!)

Bridge Rectifier with Filter

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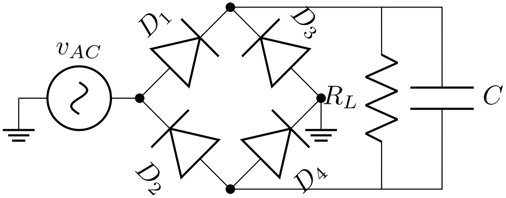
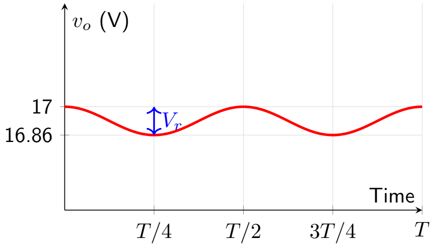
Filtered Bridge Rectifier:



Output Waveform:



Key Difference:
Ripple frequency is **2**f

$$V_r \approx \frac{V_p}{2fR_LC}$$

Ripple is **half** that of half-wave rectifier with same C!

Design Example:
Same parameters as before, but $f \to 2f$:

$$V_r = \frac{17}{2 \times 60 \times 2200 \times 470 \times 10^{-6}} = 0.137 \text{ V}$$

$$V_{DC} = 17 - \frac{0.137}{2} = 16.93 \text{ V}$$

Need for Voltage Regulation

The Problem:

- Rectifier output varies with:
  - Input voltage changes
  - Load current changes
  - Ripple voltage
- Most circuits need stable DC
- Example: Logic circuits need $\pm 5\%$ tolerance

The Solution:
Voltage regulator:

- Maintains constant output voltage
- Compensates for input variations
- Compensates for load variations
- Types: Linear, switching, Zener

Performance Metrics:

- **Load regulation**: how much V_o changes with load
- **Line regulation**: how much V_o changes with input
- **Efficiency**: P_{out}/P_{in}

Zener Diode Shunt Regulator

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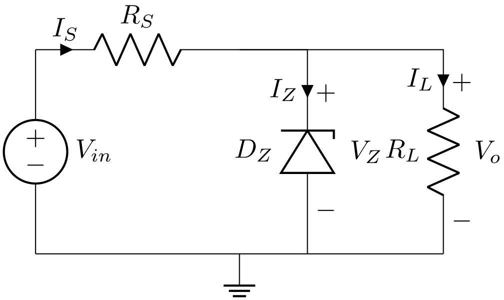
Basic Shunt Regulator:



Operation Principle:

- Zener maintains constant V_Z
- R_S drops excess voltage
- Zener absorbs current variations
- $I_S = I_Z + I_L$ (KCL)

Equations of Note:

Series resistor current:

$$I_S = \frac{V_{in} - V_Z}{R_S}$$

Kirchhoff's current law:

$$I_Z = I_S - I_L$$

Zener power dissipation:

$$P_Z = V_Z \cdot I_Z$$

Design Constraints:

- $I_Z \geq I_{Z,min}$ (stay in breakdown)
- $P_Z \leq P_{Z,max}$ (power rating)
- Worst case: max I_L, min V_{in}
- Best efficiency at full load

Shunt Regulator Design Example

Design Specifications:

- Output: $V_o = 5.1$ V (use 5.1 V Zener)
- Input: $V_{in} = 12$ V (from rectifier)
- Load: $I_L = 0$ to 50 mA
- Zener: $I_{Z,min} = 5$ mA, $P_{Z,max} = 0.5$ W

Design Process:

Step 1: Find maximum safe I_Z

$$I_{Z,max} = \frac{P_{Z,max}}{V_Z} = \frac{0.5}{5.1} = 98 \text{ mA}$$

Step 2: Choose I_S for no-load condition:
At no load, $I_Z = I_S$, so choose $I_S = 90$ mA (safe margin below 98 mA)

Step 3: Calculate R_S

$$R_S = \frac{V_{in} - V_Z}{I_S} = \frac{12 - 5.1}{0.09} = 76.7\ \Omega$$

Step 4: Verify operation at both extremes
At no load ($I_L = 0$):

$$I_Z = I_S = 90 \text{ mA}$$
$$P_Z = 5.1 \times 0.09 = 459 \text{ mW}$$

At full load ($I_L = 50$ mA):

$$I_Z = 90 - 50 = 40 \text{ mA}$$
$$> I_{Z,min} = 5 \text{ mA}$$

Regulation Performance

Load Regulation:
Measures output voltage change with load current:

$$\text{Load Reg} = \frac{V_{o,no-load} - V_{o,full-load}}{V_{o,full-load}} \times 100\%$$

Affected by:

- Zener dynamic resistance r_z
- Series resistance R_S
- Load current range

Line Regulation:
Measures output voltage change with input voltage:

$$\text{Line Reg} = \frac{\Delta V_o}{\Delta V_{in}} \times 100\%$$

Efficiency:

$$\eta = \frac{P_o}{P_{in}} = \frac{V_o I_L}{V_{in} I_S} \times 100\%$$

Key Points:

- ☹ Shunt regulators have poor efficiency
- ☹ Power wasted in R_S and Zener
- ☺ Simple and inexpensive
- ☺ Good for low-power applications

Summary: Diode Applications

Rectifier Circuits:

Half-Wave:

- $V_{DC} = V_p/\pi \approx 0.318V_p$
- Ripple frequency $= f$
- Low efficiency

Bridge (Full-Wave):

- $V_{DC} = 2V_p/\pi \approx 0.637V_p$
- Ripple frequency $= 2f$
- Better efficiency

Filtering:

- Capacitor smooths output
- $V_r \approx V_p/(fR_LC)$
- Larger C reduces ripple

Voltage Regulation:

Zener Shunt Regulator:

- Maintains constant output
- $I_S = I_Z + I_L$
- $R_S = (V_{in} - V_Z)/I_S$
- Check power dissipation

Performance:

- Load regulation: ΔV_o with ΔI_L
- Line regulation: ΔV_o with ΔV_{in}
- Efficiency: typically 20-50%