EE Dept, IIT Bombay
Academic Year: 2025-2026, Semester I (Autumn)

Course: MS101 Makerspace

EE Lecture 5
Diode Circuits

Topics
Rectifier Circuits
Unregulated Power Supply
Regulated Power Supply
Clipping and Clamping Circuits

Reference: AS Sedra and KC Smith, Microelectronic Circuits, 7th ed., Oxford University Press, 2015. Ch. 4.

1. Rectifier Circuits

- Rectifier circuits convert an AC voltage to a DC voltage.
- Most rectifier circuits use *pn* junction diodes as they have different voltage-current characteristic in the forward-bias and reverse-bias conditions.
- Half-wave and full-wave rectifiers

  - An AC voltage has alternating positive and negative half cycles.

  - Half-wave rectifiers output only one of the two half cycles, either positive or negative, of the input voltage.

  - Full-wave rectifiers give the same polarity, either positive or negative, output voltage in both half cycles of the input voltage.

  - A half-wave rectifier needs a single diode. Full-wave rectifiers use two or more diodes.

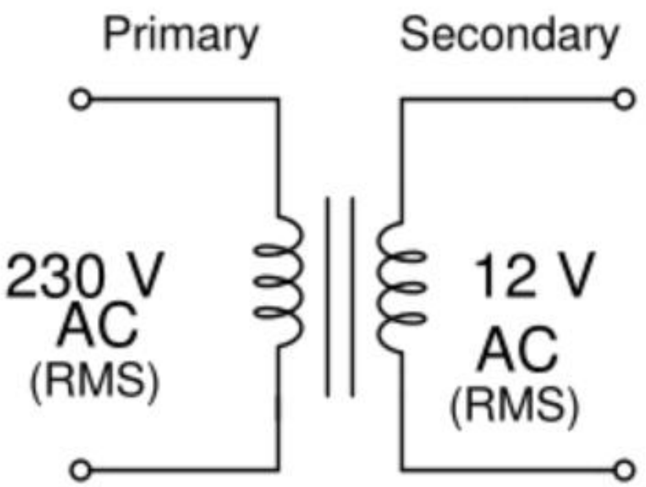
- Rectifier Applications: (i) instrumentation and communication circuits using low-current and high-frequency diodes; (ii) conversion of AC power to DC power using high-current diodes.

- Rectifiers are often used to obtain a low-voltage DC supply for powering electronic circuits from AC mains. In these applications, a transformer is used to lower the input AC voltage before rectification.

- A step-down transformer is shown in the figure, with the input applied on the primary side and the output taken from the output side.

  (input voltage) / (output voltage) = (number of primary winding turns) / (number of secondary winding turns).

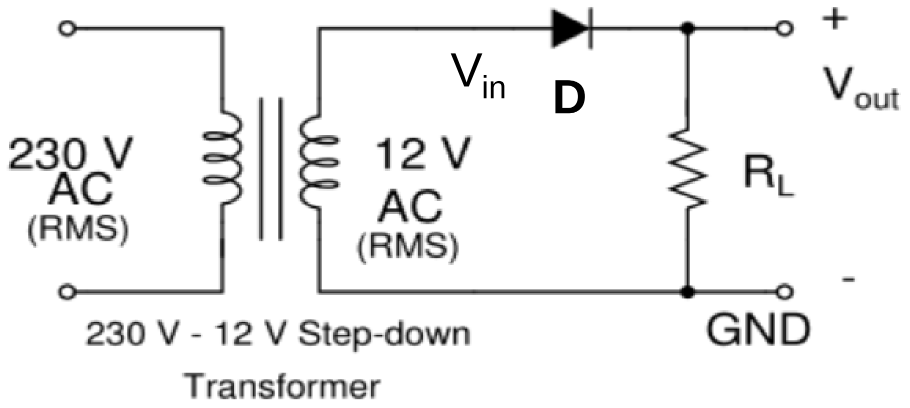
  A step-down transformer becomes step-up by changing the input and output sides.

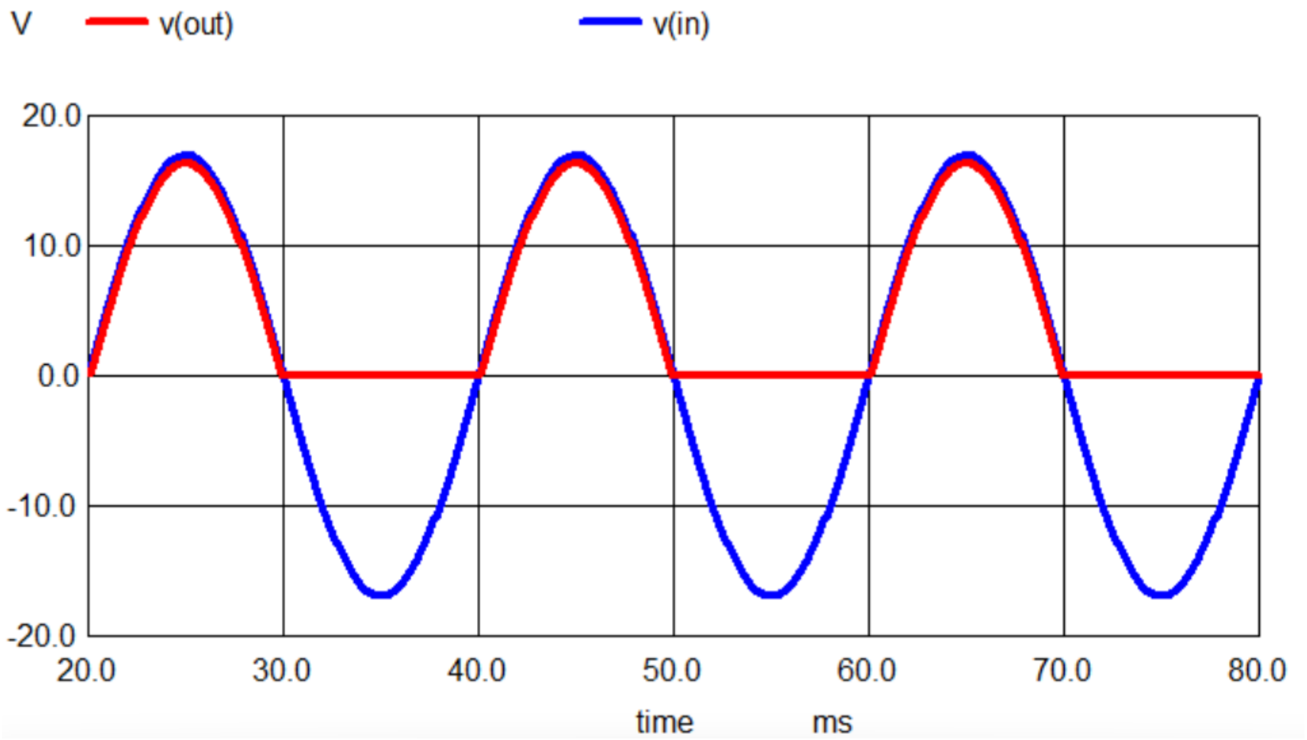


230 V - 12 V Step -down Transformer

1.1 Half-wave Rectifier

Half-wave rectifier with step-down transformer at the input



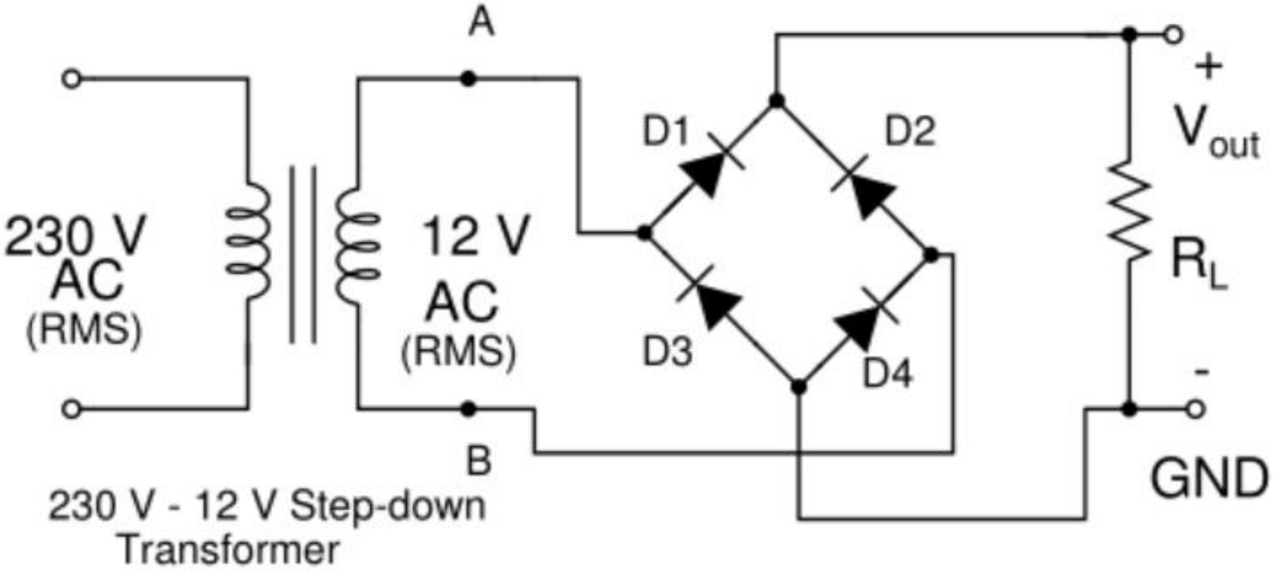


- $V_{in} > 0$: D is forward biased. $V_{in} < 0$: D is reverse biased.
- The output voltage polarity is reversed if the diode polarity is reversed.
- A practical diode's forward voltage drop changes with the current, with the maximum drop of 0.6-0.8 V.

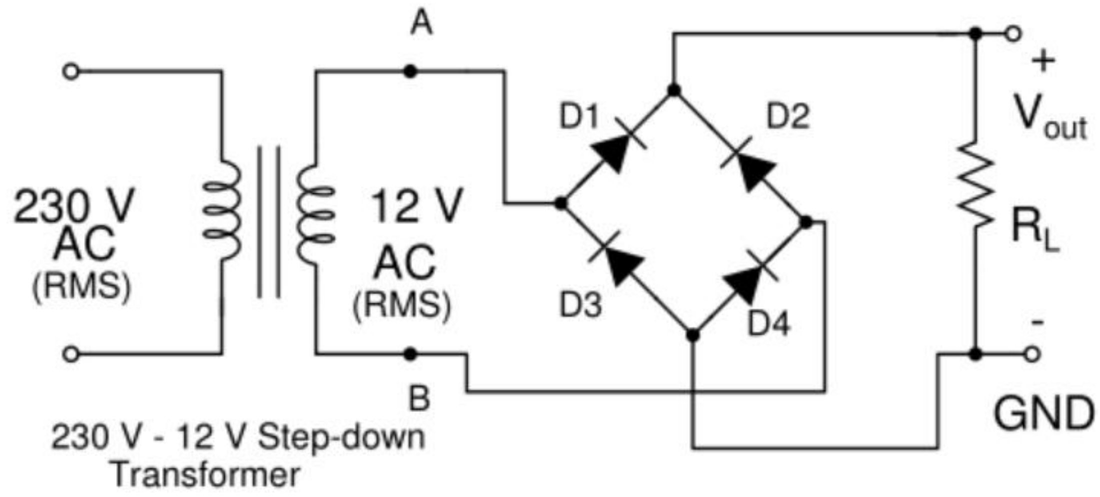
V_{in} and V_{out} waveforms assuming a practical diode with finite forward voltage drop. Note that the maximum voltage drop happens at the peak.

1.2 Full-Wave Bridge Rectifier

- Full-wave bridge rectifier: a transformer and four diodes.
- Two diodes are in the current path in each half cycle of the input voltage.
- $v_{AB} > 0$: Current flows through D1, R_L, & D4. D2 and D3 are reverse biased.
- $v_{BA} > 0$: Current flows through D2, R_L, & D3. D1 and D4 are reverse biased.
- v_{out} is always positive, with two diode drops between the input and output voltages.
- Neither A nor B is at the same potential as the output GND terminal. Neither should get accidentally connected to GND.



Note: There is another full-wave rectifier using two diodes and a center-tapped transformer. It is not in much use now.

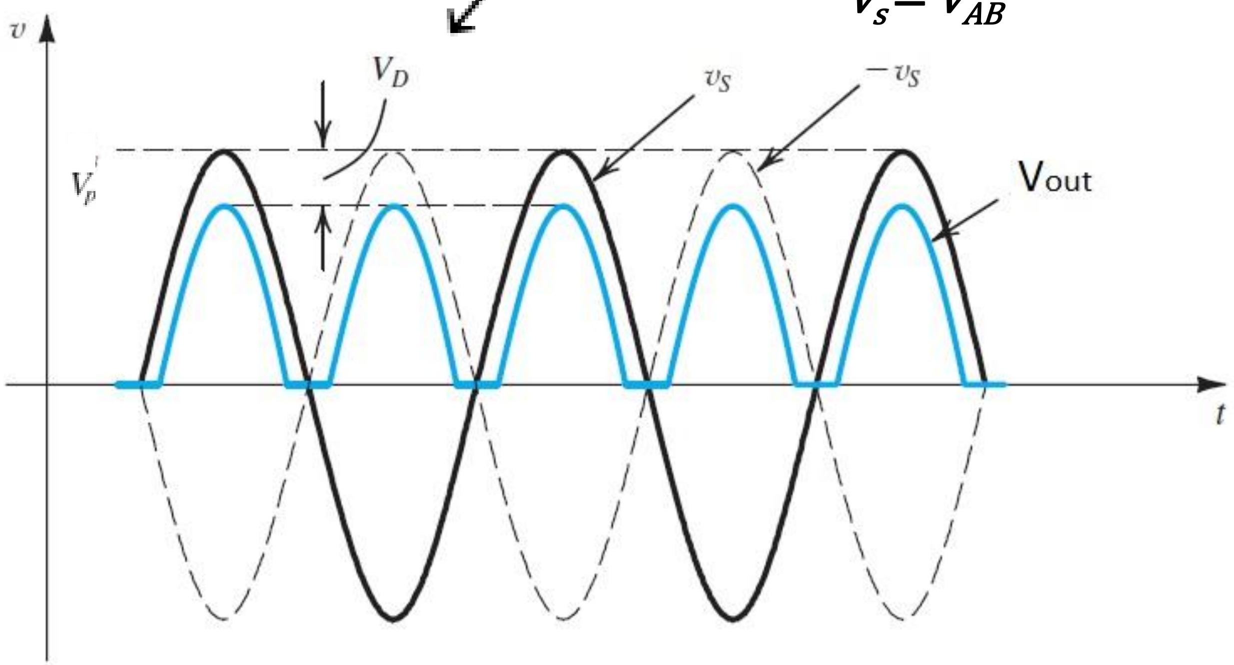


- Current flow during positive half cycle ($v_{AB} > 0$): terminal A → D1 → R_L → D4 → terminal B.
  D2 & D3 do not conduct.

- Current flow during negative half cycle ($v_{AB} < 0$): terminal B → D2 → R_L → D3 → terminal A.
  D1 and D4 do not conduct.

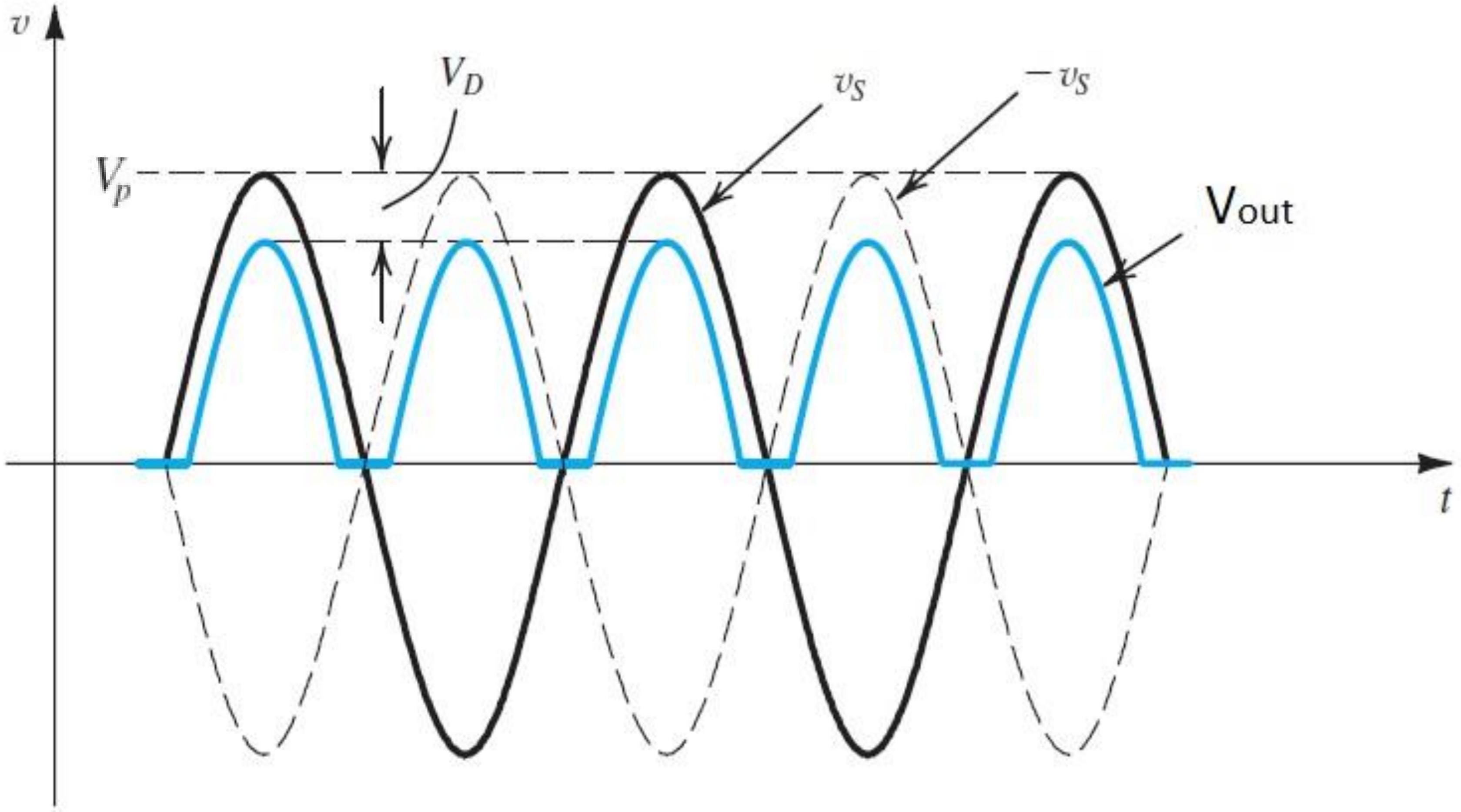
V_D: voltage drop across two diodes (D1&D4, D3& D2)

$v_s = v_{AB}$



Full-Wave Rectifier: Input and Output Waveforms (considering diode drops).

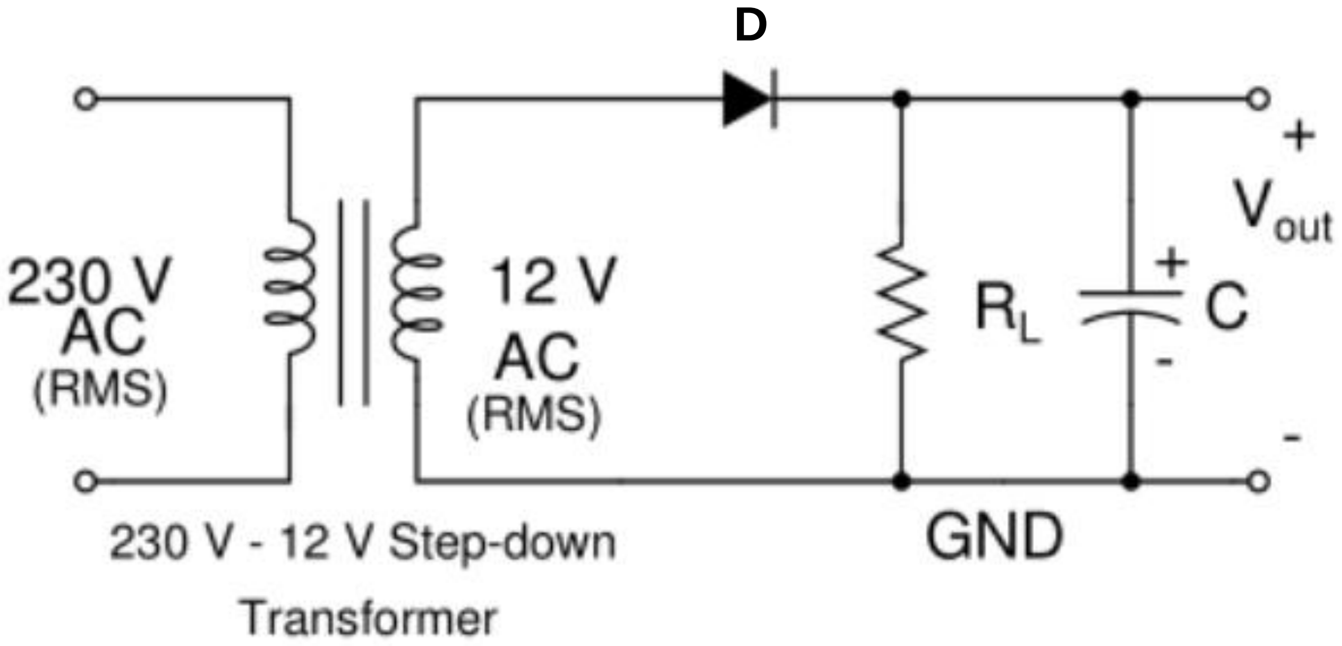
- Peak output voltage is *two diode drops* lower than the input voltage.
- Typ. diode drop = 0.5-0.8 V.
- Peak input-output difference = 1.0-1.6 V.



2. Unregulated DC Power Supply

- An unregulated DC power supply is the simplest DC power supply.
- A rectifier has a single polarity output, but it cannot be directly used as a DC supply to power electronic circuits because of its time-varying output voltage
- The variation in the output voltage is called 'ripple'. It is reduced by connecting a large value capacitor across the rectifier output. The capacitor reduces the ripple by accumulating charge when the voltage is increasing and discharging when the voltage is decreasing.
- The peak-to-peak ripple is a measure of output quality. Ideally, the output should have zero ripple.
- For a given capacitor, full-wave rectifiers have lesser ripple than the half-wave rectifiers.
- The term ‘unregulated’ indicates that the output voltage fluctuates with
  - AC input voltage fluctuation, and
  - load current fluctuation.

2.1 Half-Wave Rectifier with a Capacitive Filter

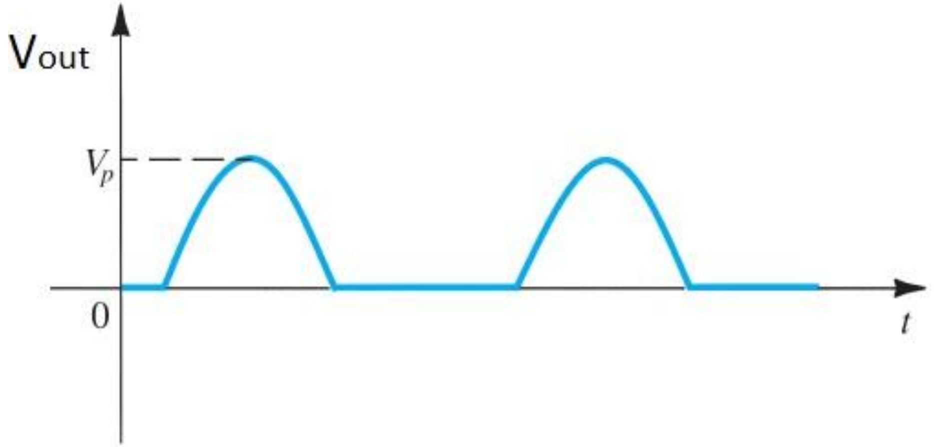


- A larger capacitor accumulates more charge and hence is more effective in reducing the ripple.
- A larger capacitor takes more current during its charging, and this current must be less than the diode's peak current rating.

- Large value capacitors are usually "electrolytic" type capacitors, with the terminals having $+$ and $-$ polarities. They must be connected across a dc voltage with matching terminal polarities.

Half-Wave Rectifier with a Capacitive Filter: Waveforms

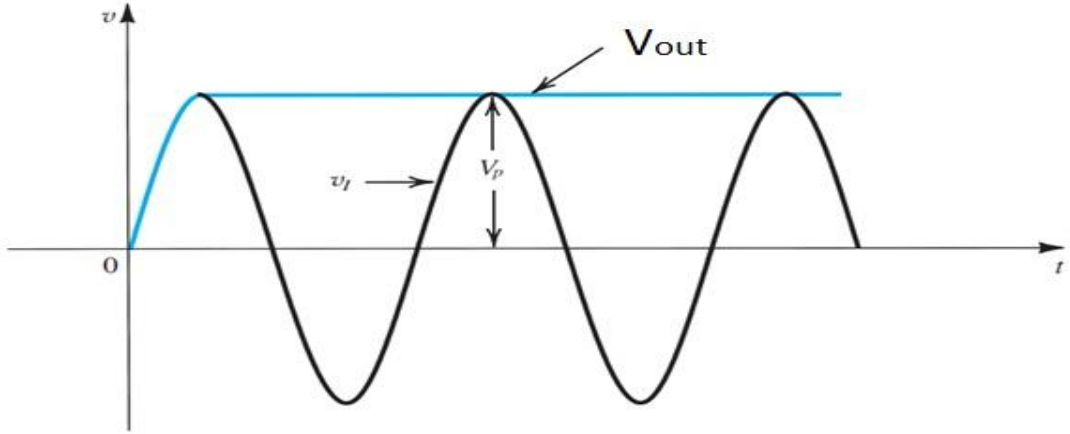
Output voltage waveform with $C = 0$.
Peak-to-peak ripple = V_p.



Operation with a finite C and no load ($R_L = \infty$).

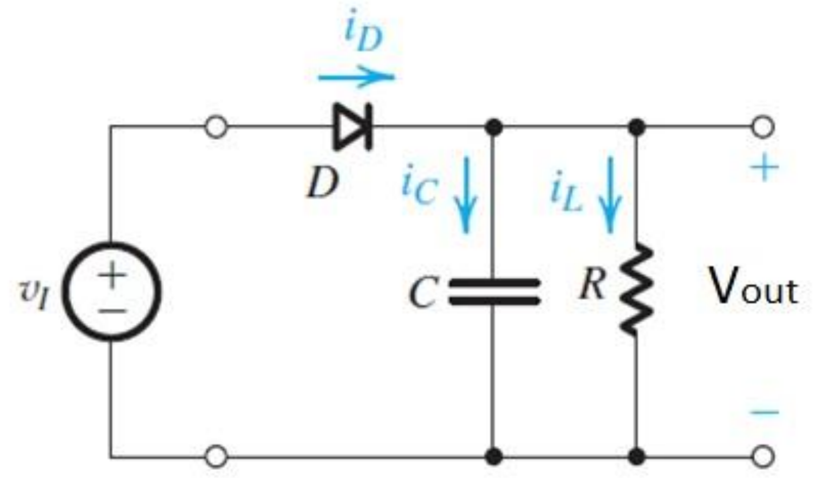
The capacitor gets charged to the peak voltage and holds it.

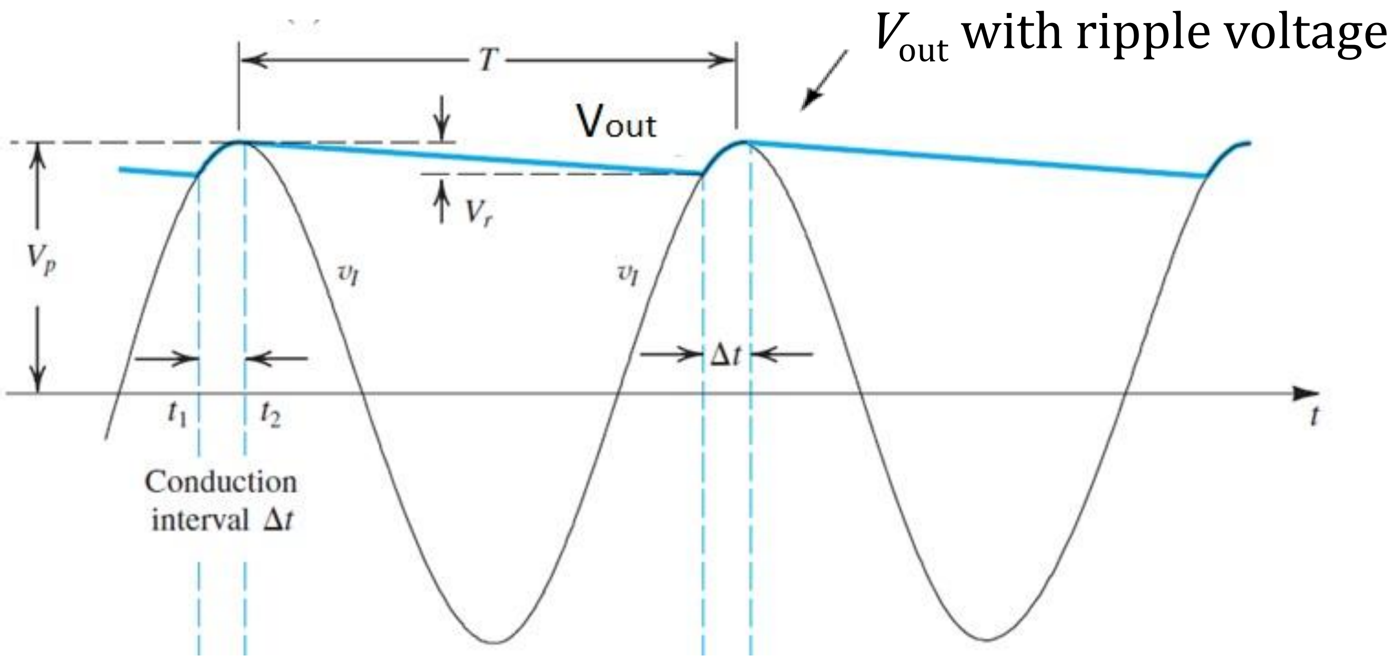
Peak-to-peak ripple = 0, i.e. V_{out} is a constant dc voltage.



Operation with C across the Load

- C charges during Δ_t, and discharges during (T-Δ_t).
- Peak-to-peak ripple V_r increases with the load current i_L.



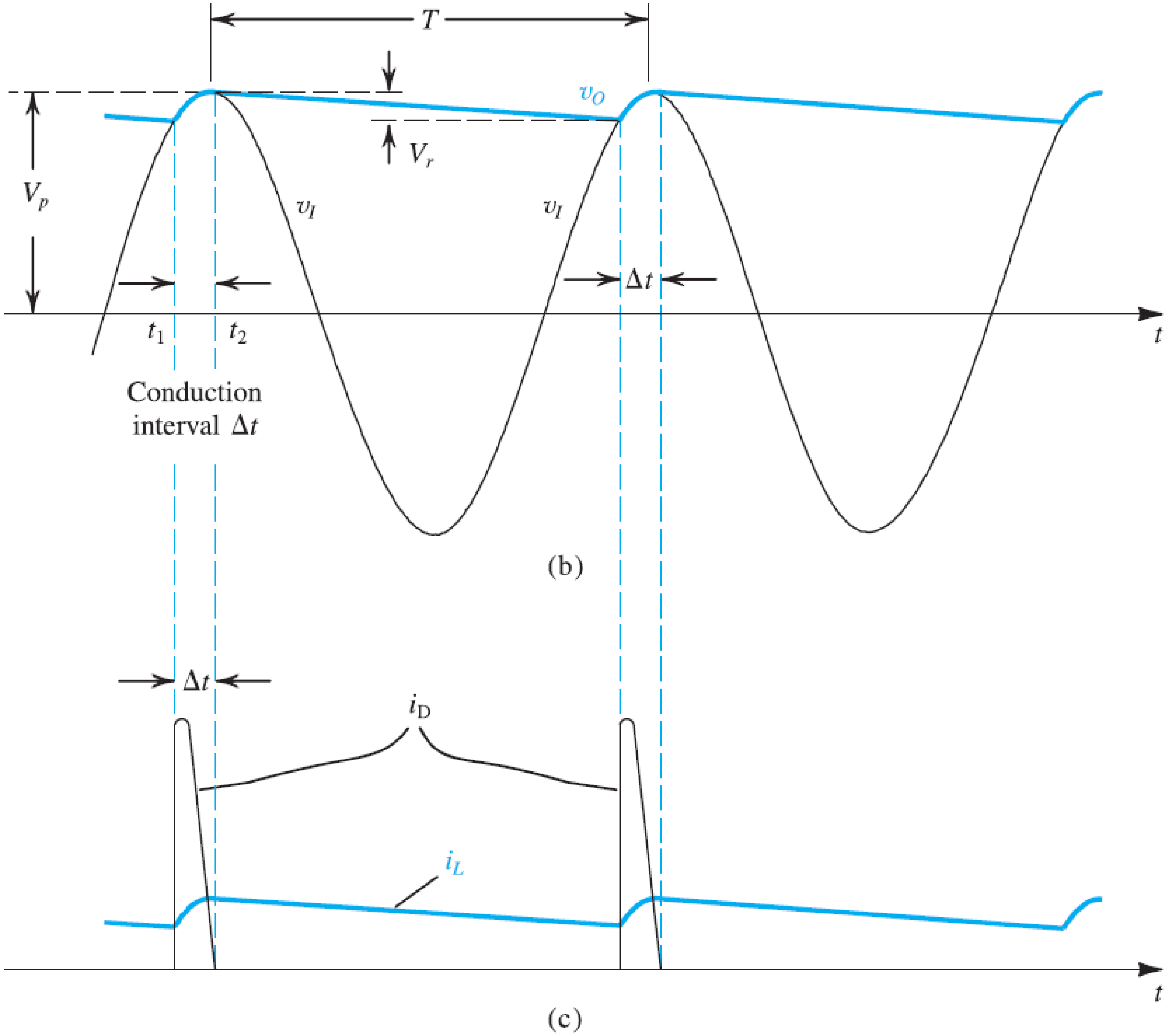


Voltage & Current Waveforms

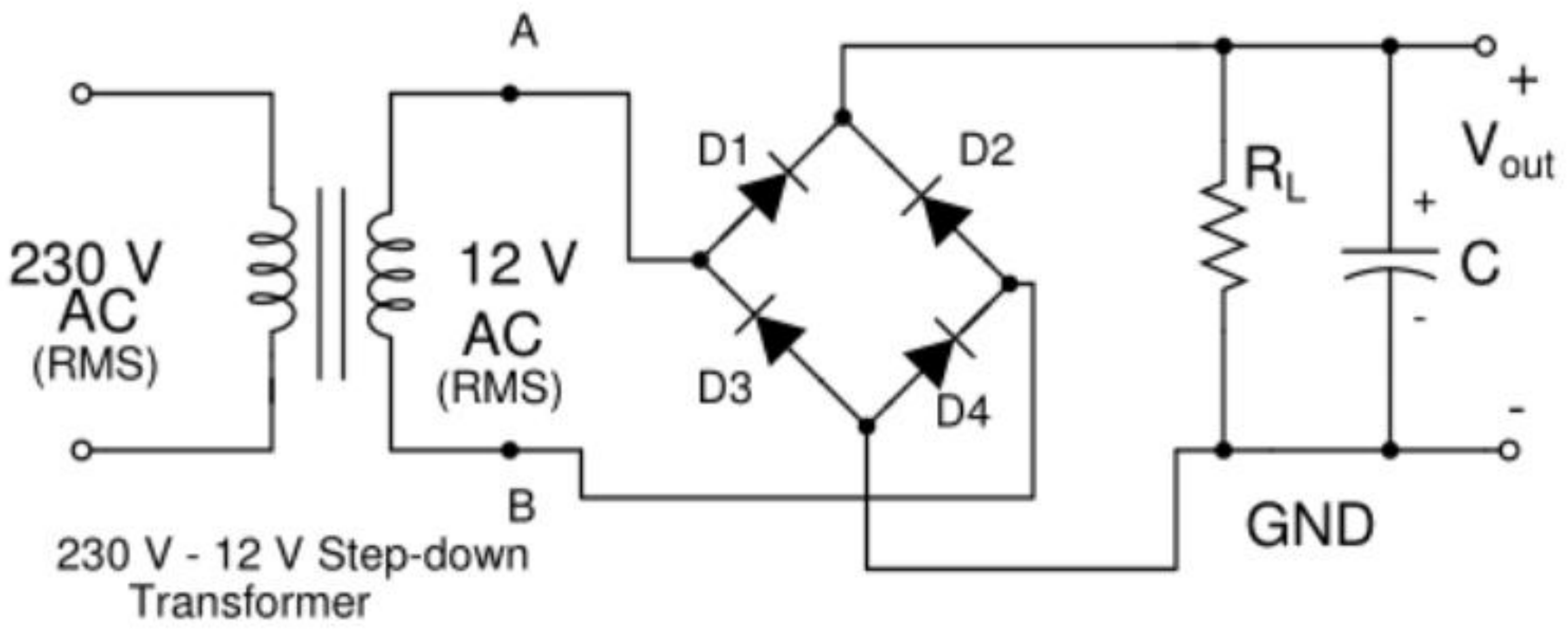
- Ripple can be decreased by increasing C.
- For a given i_L, as $C\uparrow$,

  $\Delta_t\downarrow \rightarrow \; i_D\uparrow\uparrow$.

  Therefore, the C value is limited by the diode's peak current rating.
- Half-wave rectifiers with C are not much used for power supply because full-wave rectifiers with C have lesser ripple.



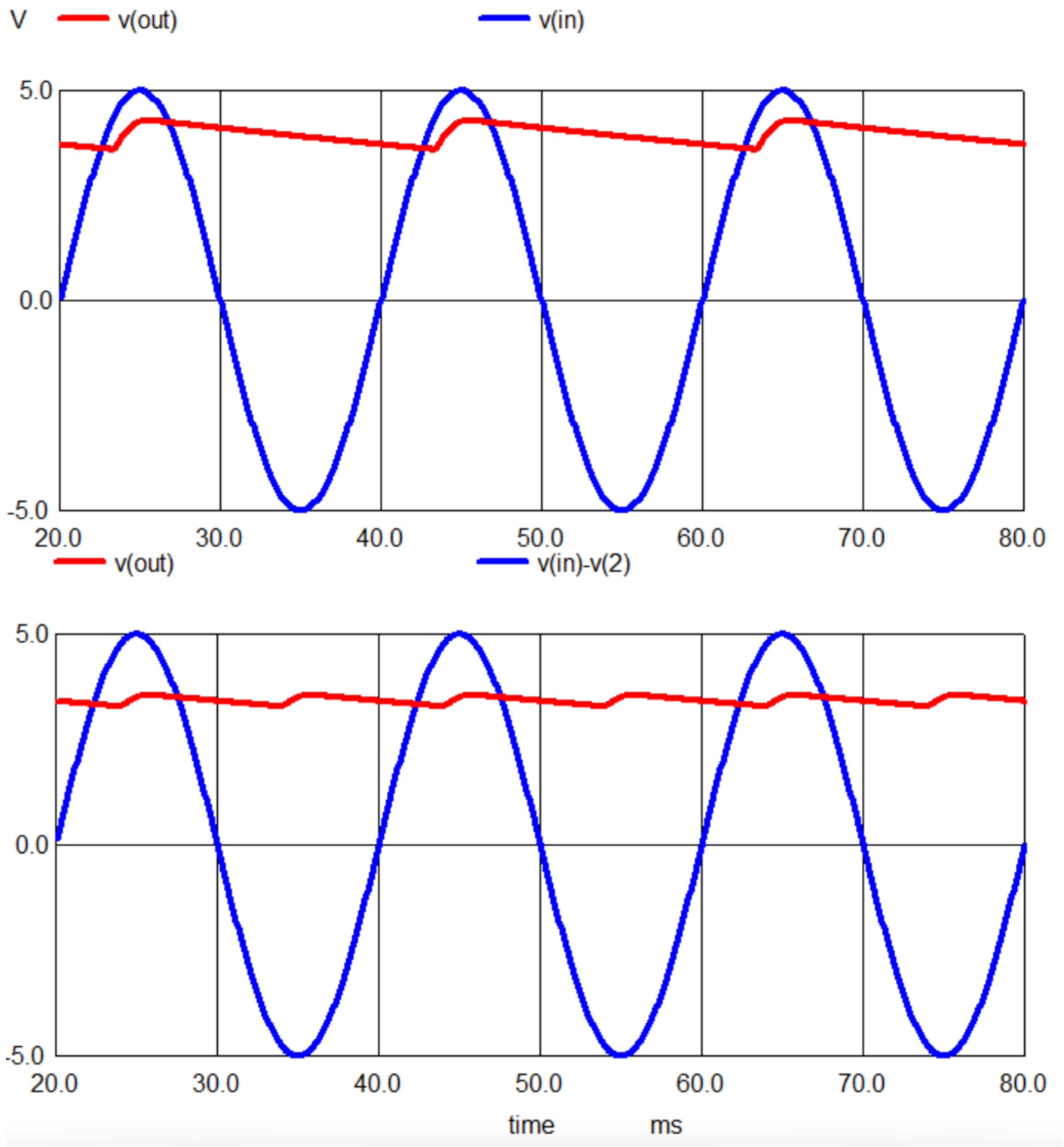
2.2 Full-Wave Bridge Rectifier with a Capacitive Filter



With a full-wave rectifier, C is charged every half cycle of the input voltage. Therefore, the peak-to-peak ripple gets reduced to nearly half that of half-wave rectifier for the same load current and capacitor.

Output with a Full-wave Rectifier & C

- C charges & discharges every half cycle.
- The discharge interval is almost half that in the half-wave rectifier case. Therefore peak-to-peak ripple is nearly halved.
- Example waveforms with $(v_i)_{peak} = 5$ V, $R_L = 1$ kΩ, $C = 100$ μF.



Half-wave rectifier

Full-wave rectifier

2.3 Problems of Unregulated Power Supply

- Output voltage changes when the AC input voltage changes, and also when the load current changes.
- The output ripple increases with increase in the load current.
- Ripple for a given load current can be reduced by increasing C. However, increase in C increases the peak current through the diodes. Increasing it beyond a certain value can cause diode damages.

3. Regulated Power Supply

- A regulated power supply provides a nearly constant output voltage for large input voltage and load current variations.
- Characterization of the output voltage variations of a power supply
  - Line regulation = (Change in the output voltage) / (Change in the input voltage), for a given load current

    = $(\Delta v_o / \Delta v_i)$ for a constant i_L. Usually expressed as %.
  - Load regulation = (Change in the output voltage for the load current changed from the minimum to maximum) / (Output voltage at a nominal load current)

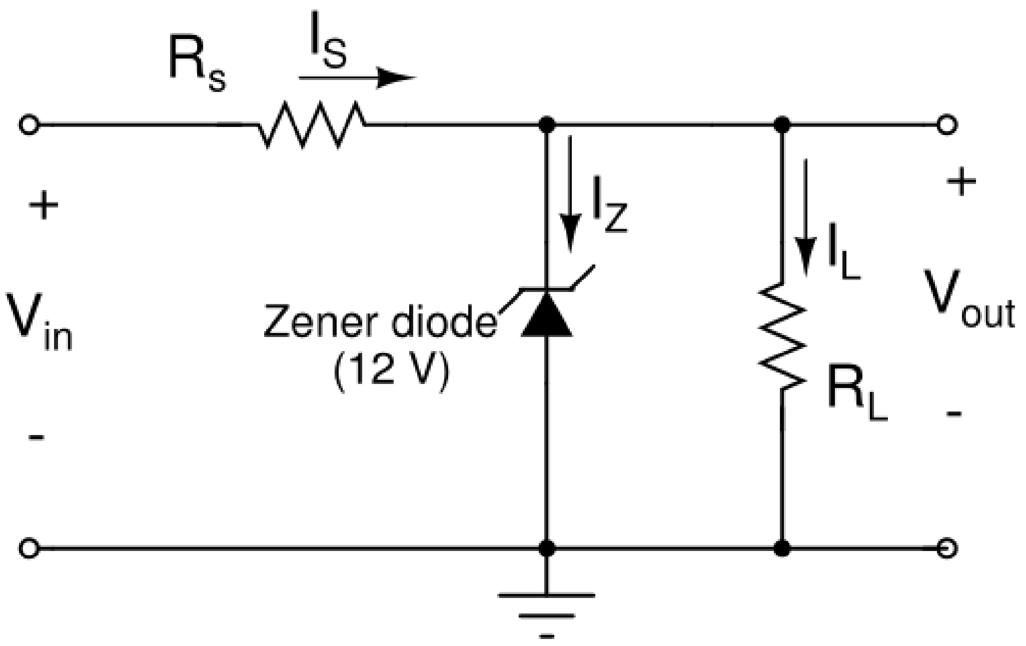
    = $[v_o(i_{Lmax}) - v_o(i_{Lmin})] / v_o(i_{Lnom})$. Usually expressed as %.

    Another characterization of output voltage change with load current:

    Output resistance = $|\Delta v_o / \Delta i_L|$ for a given input voltage v_i.
  - Note that these quantities should be small for a good power supply.

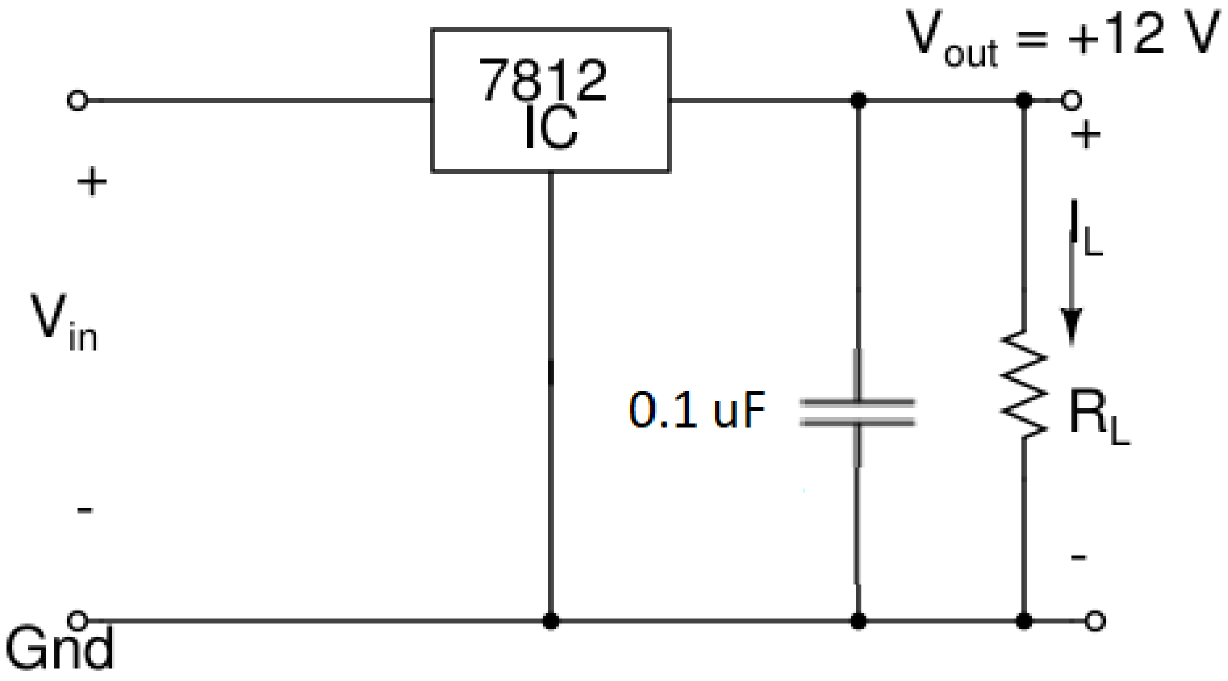
3.1 Two Regulated Supply Solutions from an Unregulated Supply

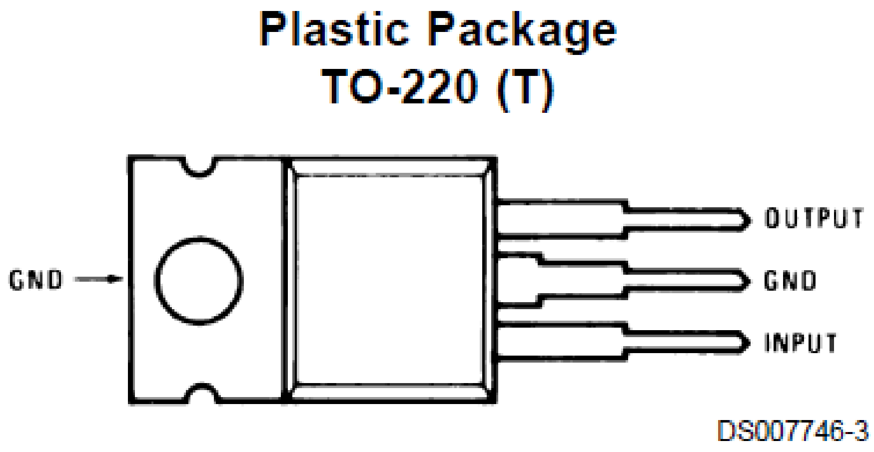
- *Zener Diode Regulator*
  - A Zener diode, with its Zener voltage same as the required output voltage is connected across the load to obtain a constant load voltage.
  - V_{in} is the unregulated supply output. R_s limits the Zener diode current. It dissipates power and results in low efficiency. These regulators are useful only for small variations in the input voltage & load current.



- *Regulators Using Voltage Regulator IC (integrated circuit)*
  - A voltage regulator IC is connected between the unregulated supply output and the load. Several types of voltage regulator ICs for various voltages and load currents are available. Some types have just three terminals and are used for a fixed voltage, others can be used for an adjustable output voltage.
  - These regulators use a large number of electronic components internally. They are used for improved line and load regulation, low ripple, and high efficiency.

3.2 7812 Three-Terminal Voltage Regulator





V_{in} : 14.5 to 30 V. V_{out} : 11.5–12.5 V, 12 V typical. $I_L < 1$ A.

$\Delta V_{out} <$ 240 mV for full input voltage range. $\Delta V_{out} <$ 240 mV for full load current range.

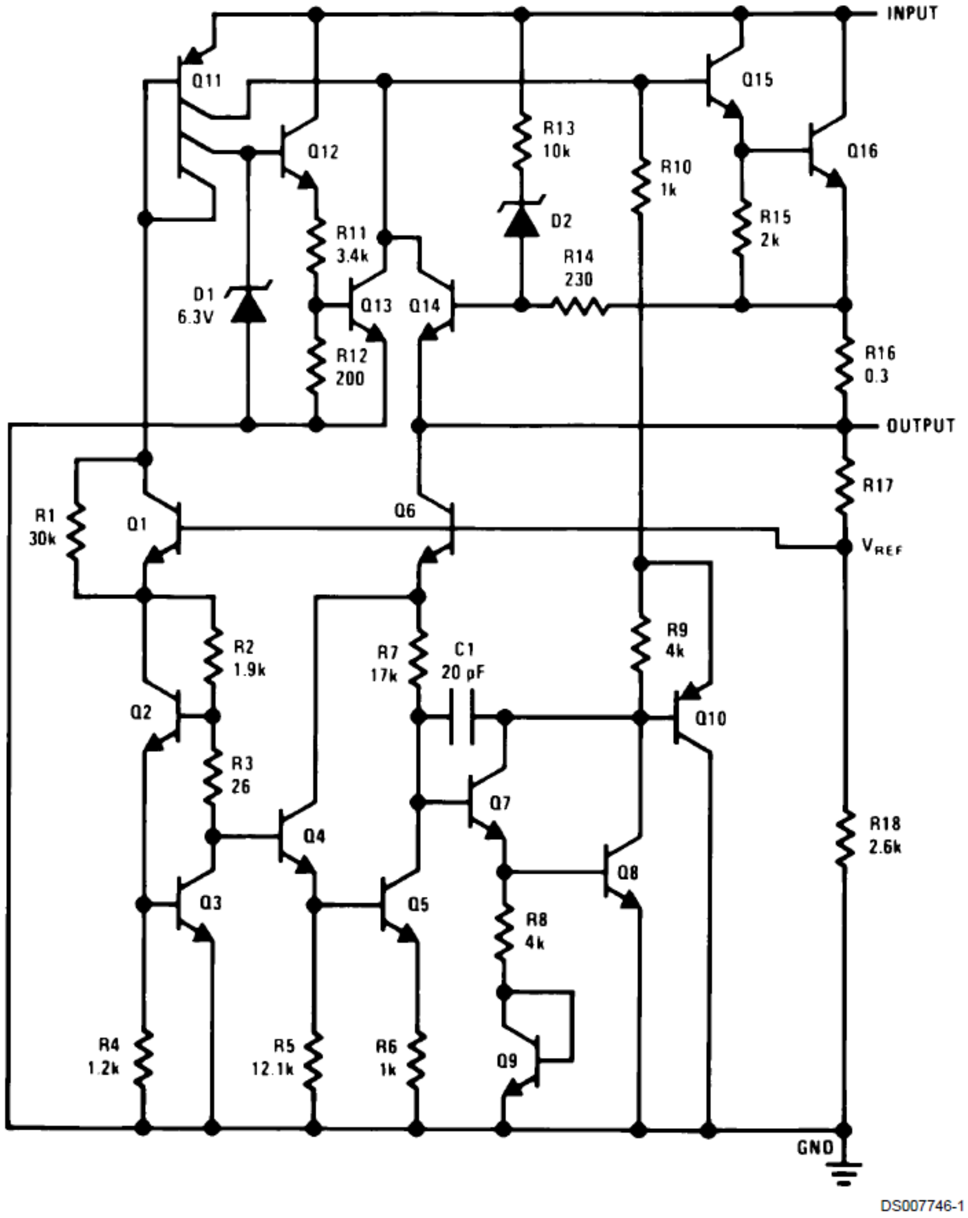
Output resistance < 18 mΩ.

Internal Circuit of the Regulator IC 7812

Major blocks

- Series-pass transistor (Q16)
- Stable Zener reference voltage
- Error amplifier
- Short-circuit protection

Source: 7812 Data sheet, National Semiconductor Corp., 2000



3.3 IC Regulator Features

- V_{out} is nearly constant over a large range of V_{in} and I_{L}.
- Minimum V_{in} to the IC regulator: $V_{\text{out}} + 2\text{–}3$ V (typical)
- The regulator IC internally has a negative feedback error amplifier, which could result in instability. A small value of capacitor, typically 0.1 μF, is put at the output for stability (i.e. to prevent oscillations). This capacitor should be connected with shortest possible distance from the regulator IC leads.
- Positive and negative regulator ICs are available for several output voltages.
  - Positive regulators: Common negative terminal between the input and output.
  - Negative regulators: Common positive terminal between the input and output.

3.4 Some Commonly Used Three-Terminal Voltage Regulator ICs

- Positive Voltage Regulator ICs

  7805 : $V_{\text{out}} = 5\text{ V}$

  7806 : $V_{\text{out}} = 6\text{ V}$

  7809 : $V_{\text{out}} = 9\text{ V}$

  7812: $V_{\text{out}} = 12\text{V}$

- Negative Voltage Regulator ICs

  7905 : $V_{\text{out}} = -5\text{ V}$

  7906 : $V_{\text{out}} = -6\text{ V}$

  7909 : $V_{\text{out}} = -9\text{V}$

  7912 : $V_{\text{out}} = -12\text{ V}$

4. Clipping and Clamping Circuits

Diodes are used in waveshaping circuits for changing the shape of the voltage waveform. We will study two such circuits.

- Clipping circuits (limiting circuits) use diodes to clip (limit) the maximum or minimum of the output waveform at a given voltage.

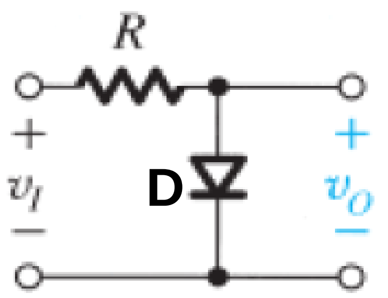
- Clamping circuits use diodes and capacitors to clamp (hold) the maximum or minimum value of the output waveform at a given DC voltage. These circuits are also known as DC restorer circuits because they introduce a DC shift.

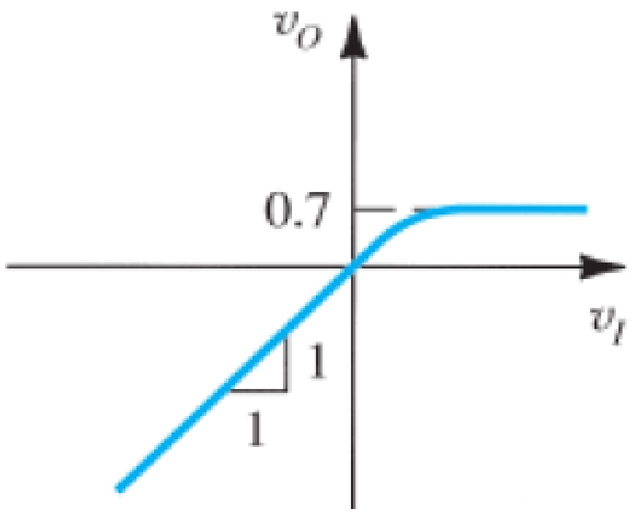
4.1 Clipping Circuits

- Clipping circuits use diodes and resistors to limit the maximum or minimum of the output waveform at a given voltage.
- A clipping circuit is described by its input-output transfer characteristic.
- Clipping circuits use a diode in the forward-biased condition to limit the output. A resistor in series with the diode limits the current through the diode. The diode is reverse-biased during the non-limiting operation.
- The transfer characteristic is usually obtained assuming a constant diode drop ($V_D \approx$ 0.7 V) in the forward-biased condition.
- Some clipping circuits use Zener diodes, operating in forward-biased and reverse breakdown conditions.

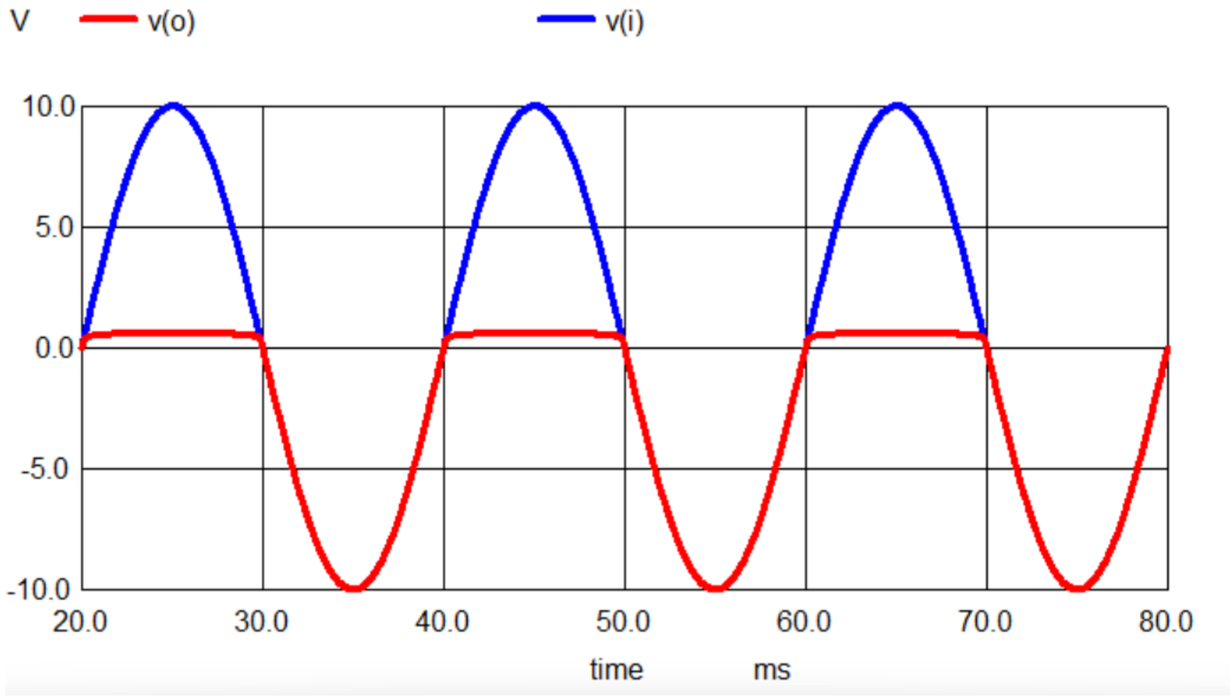
Peak Limiting Circuit

- $v_I < 0$: D is reverse biased, with almost no current through it. Voltage drop across R is zero. Therefore, $v_O = v_I$.
- $0 < v_I < 0.5$ V: D is forward biased but still in cutoff with negligible current through it. Therefore, $v_O \approx v_I$.



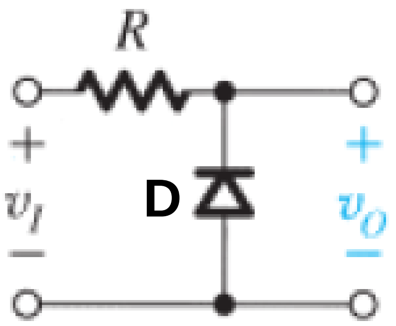


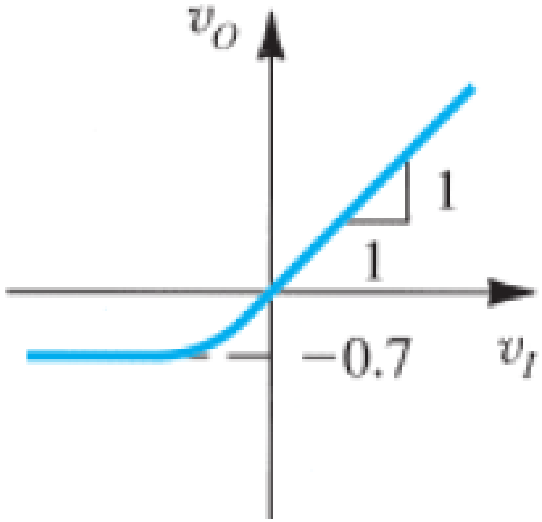
- As v_I goes above 0.5 V, D turns on, the current through it rapidly increases with corresponding increase in the voltage drop across R, eventually limiting v_O to 0.7 V.
- The voltage waveform above +0.7 V is clipped in the output.

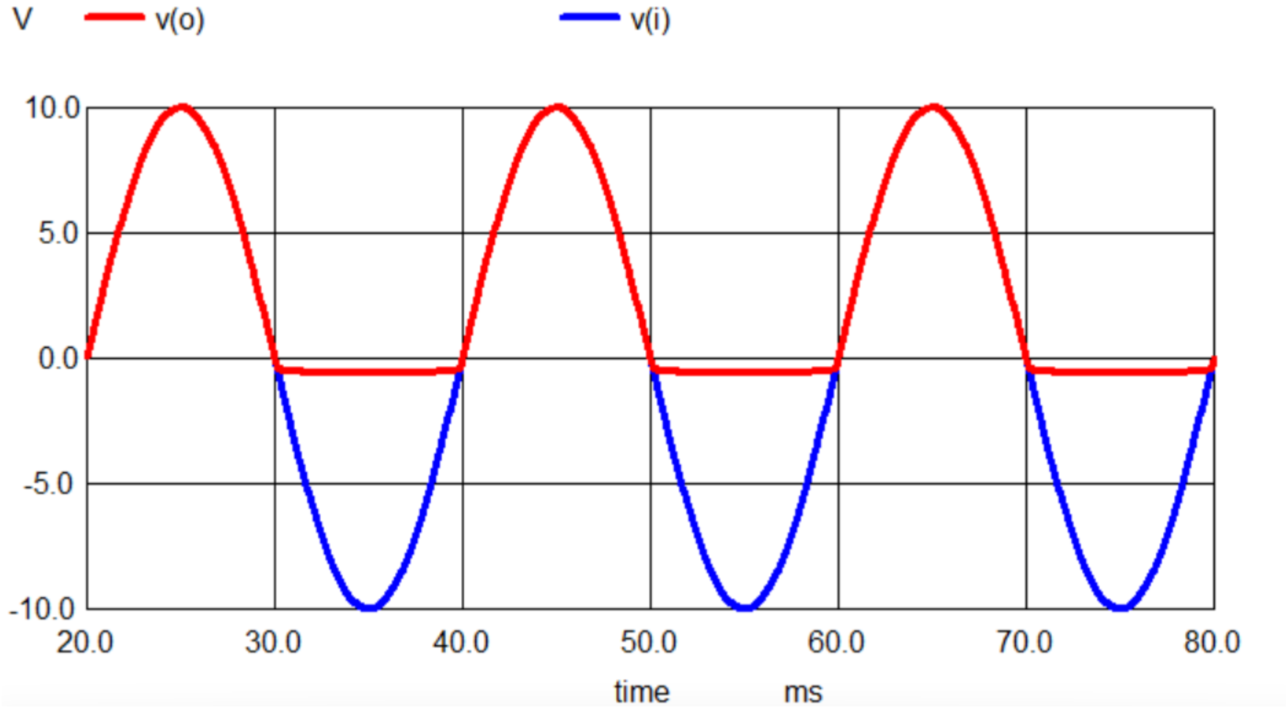


Valley Limiting Circuit

- The diode in the peak limiter is reversed for valley limiter..
- $v_I > 0$: $v_O = v_I$.
- $0 < v_I < –0.5$ V: $v_O \approx v_I$.
- As v_I goes below –0.5 V, D turns on, eventually limiting v_O to –0.7 V.
- The voltage waveform below –0.7 V is clipped in the output.

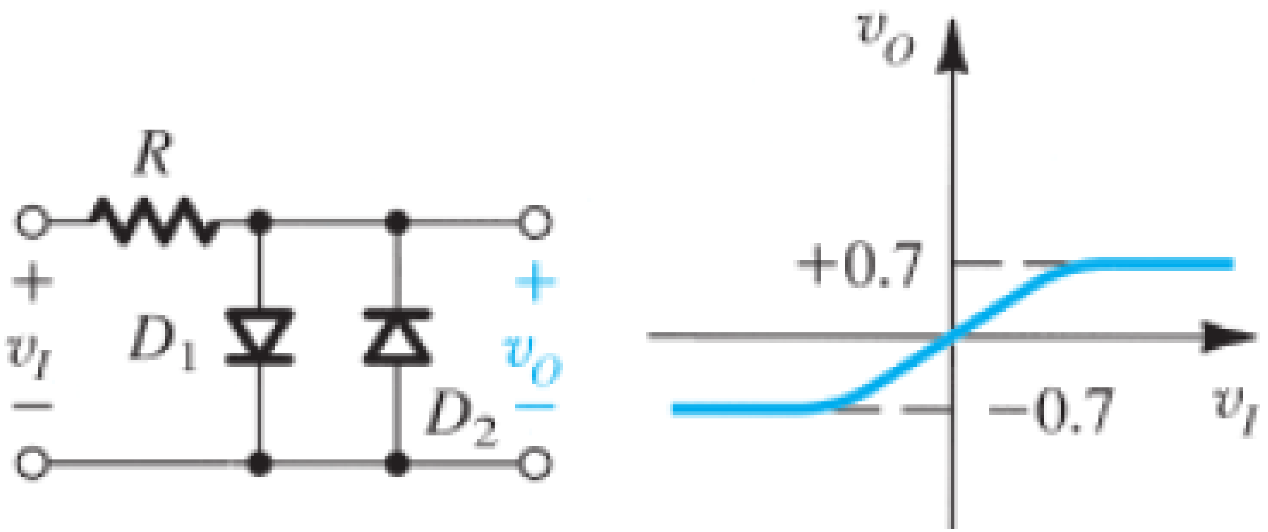


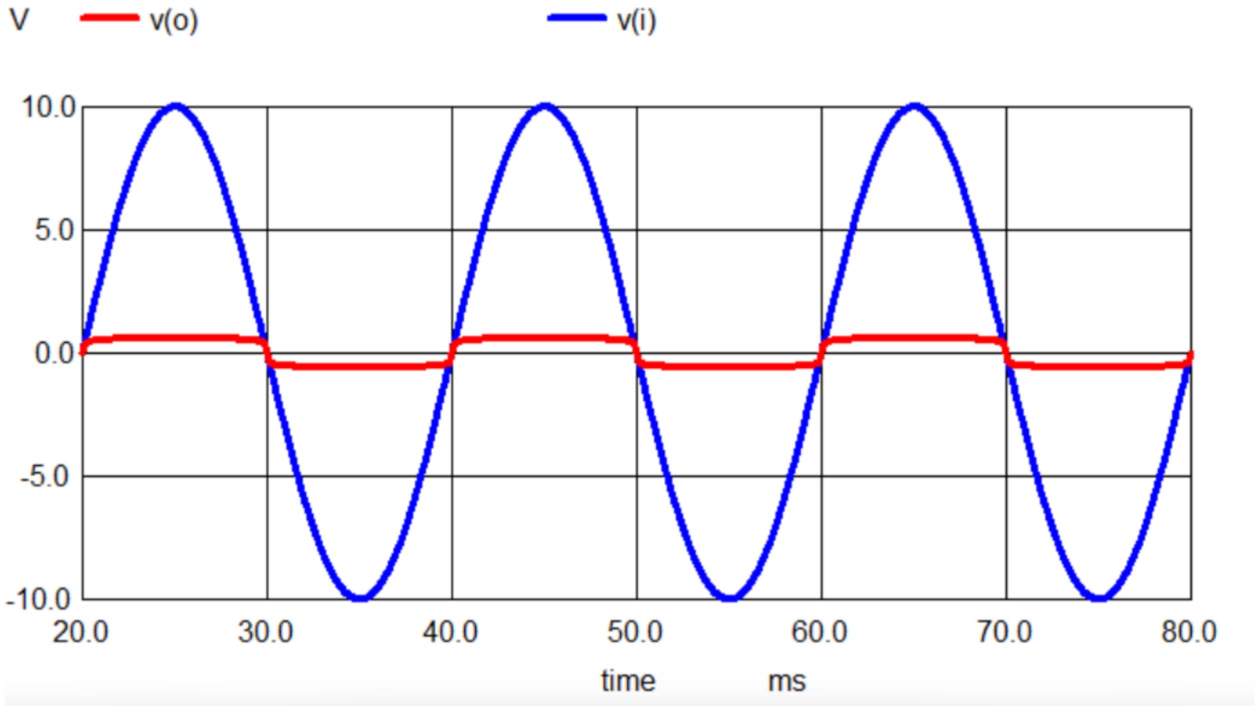




Peak and Valley Limiting Circuit (Double Limiter)

- Two diodes with opposite polarities are connected in parallel.
- $-0.5\text{ V} < v_I < 0.5\text{ V}$: Both diodes are off. Therefore, $v_O = v_I$, resulting in the linear region of the transfer characteristic.
- As v_I goes above 0.5 V, D_1 turns on and eventually limits v_O to +0.7 V. Similarly, as v_I goes below −0.5 V, D_2 turns and eventually limits v_O to −0.7 V.



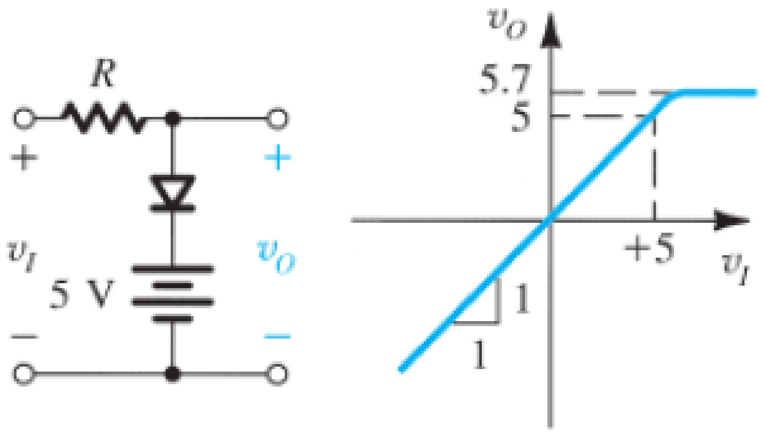


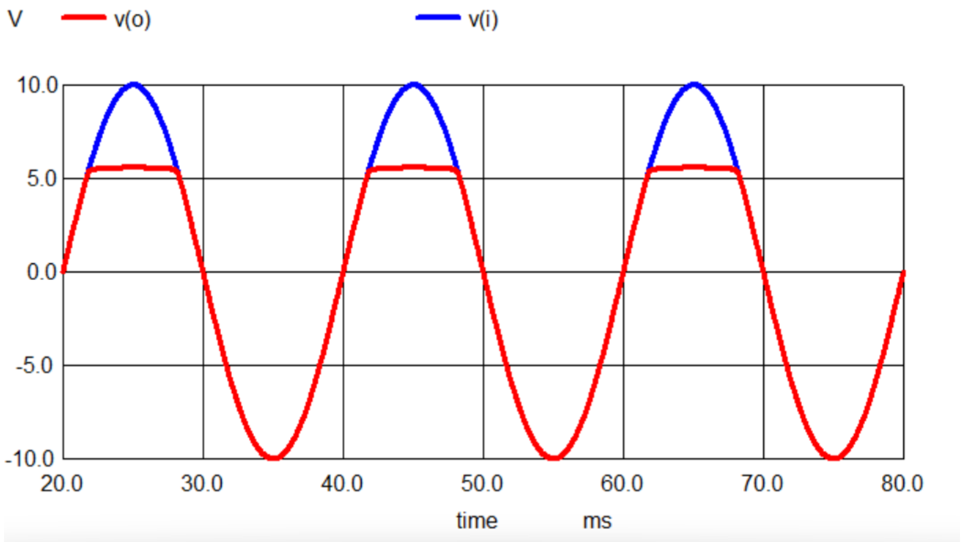
Limiters with Controlled Saturation Voltages

The saturation levels in the limiters can be controlled by using a string of diodes, a dc voltage in series with the diode, and/or Zener diodes.

Limiter with Controlled Positive Saturation Voltage

- A dc voltage in series with the diode controls the positive saturation voltage.
- With Si diode and 5 V source, v_O is limited to 5.7 V.
- Linear transfer characteristic for $v_I < 5.5$ V.

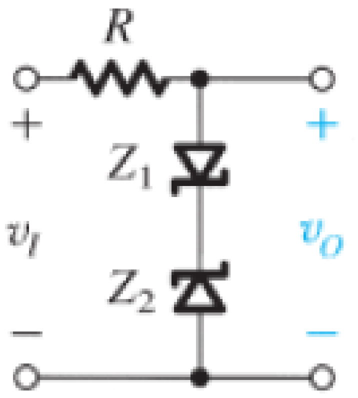


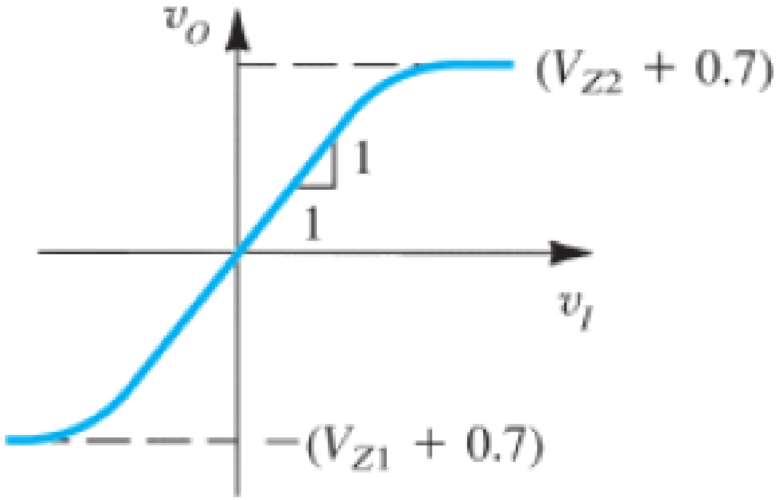


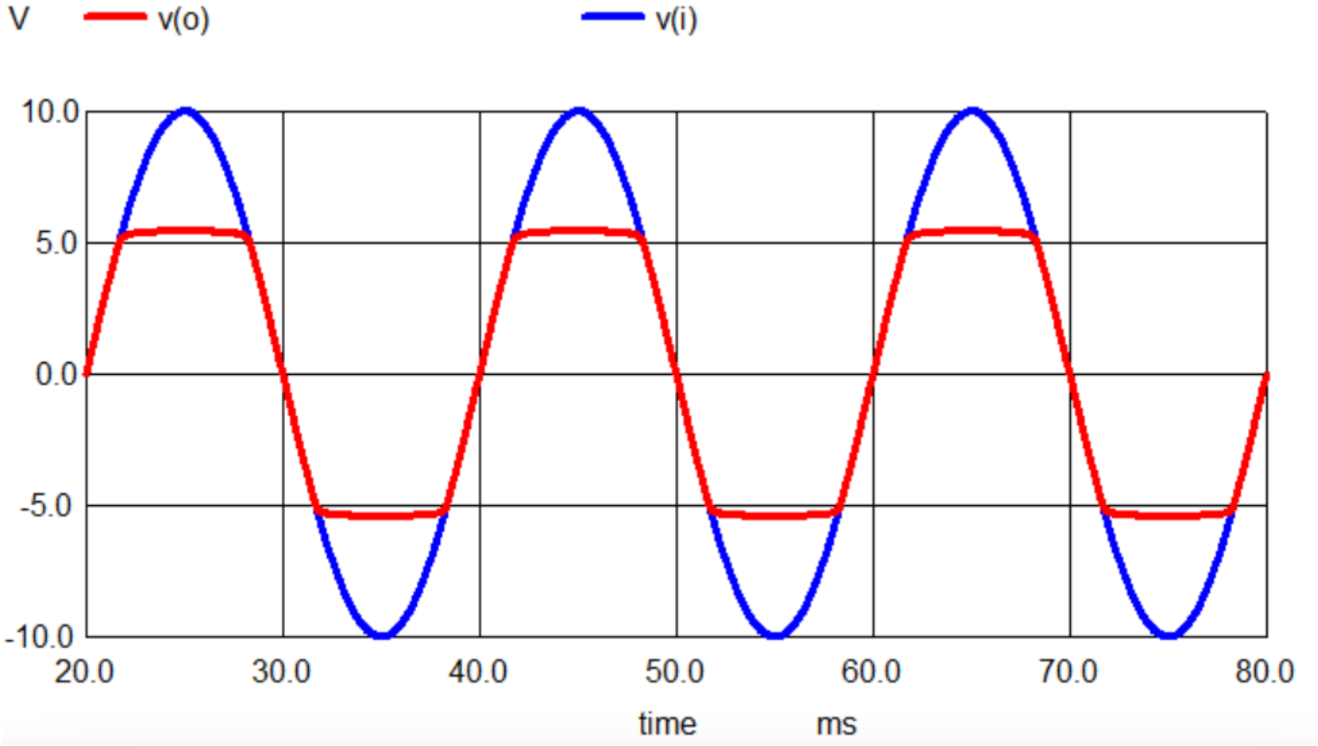
Limiter Using Zener Diodes

- Two Zener diodes in series.
- $V_{Z1} = V_{Z2} = 5$ V
- Linear region: Z1 & Z2 in cutoff.
  $-V_{Z1} - 0.5\text{ V} < v_I < V_{Z2} + 0.5$ V.
  $v_O = v_I$.
- Positive limiting: Z1 in forward bias, Z2 in breakdown.
  $v_o = V_{Z2} + 0.7$ V
- Negative limiting: Z1 in forward bias, Z2 in breakdown.

  $v_o = V_{Z2} + 0.7$ V.

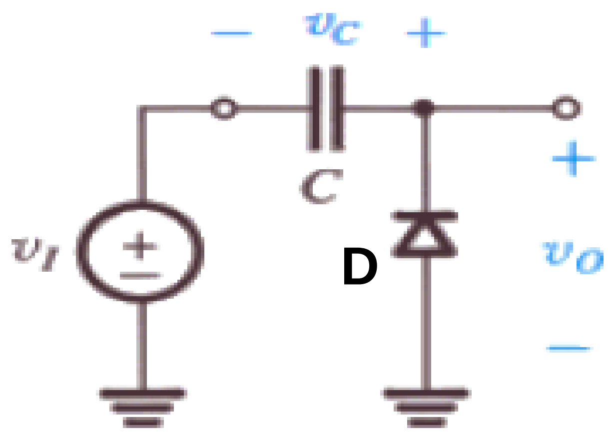






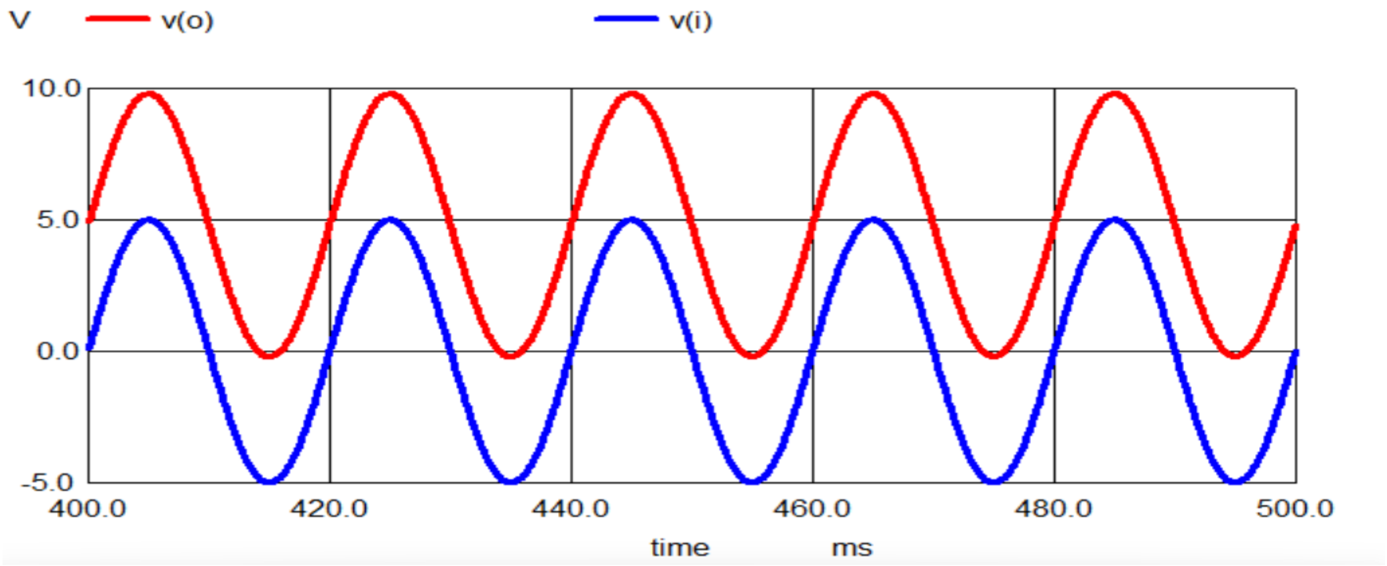
4.2 Clamping Circuits

A clamping circuit uses a diode and a capacitor to clamp (hold) the peak or valley of the output waveform at a given DC voltage by charging the capacitor to introduce a DC shift.



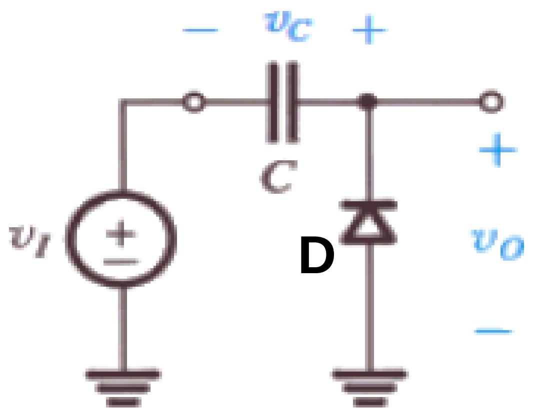
Valley Clamping Circuit

- A diode & a capacitor are used to hold the valley of a periodic waveform at zero.
- *D*, because of its polarity, turns on if v_o becomes negative & C is charged to v_C as shown and equal to the magnitude of the valley of v_i. Subsequently, *D* turns off & *C* retains its charge.

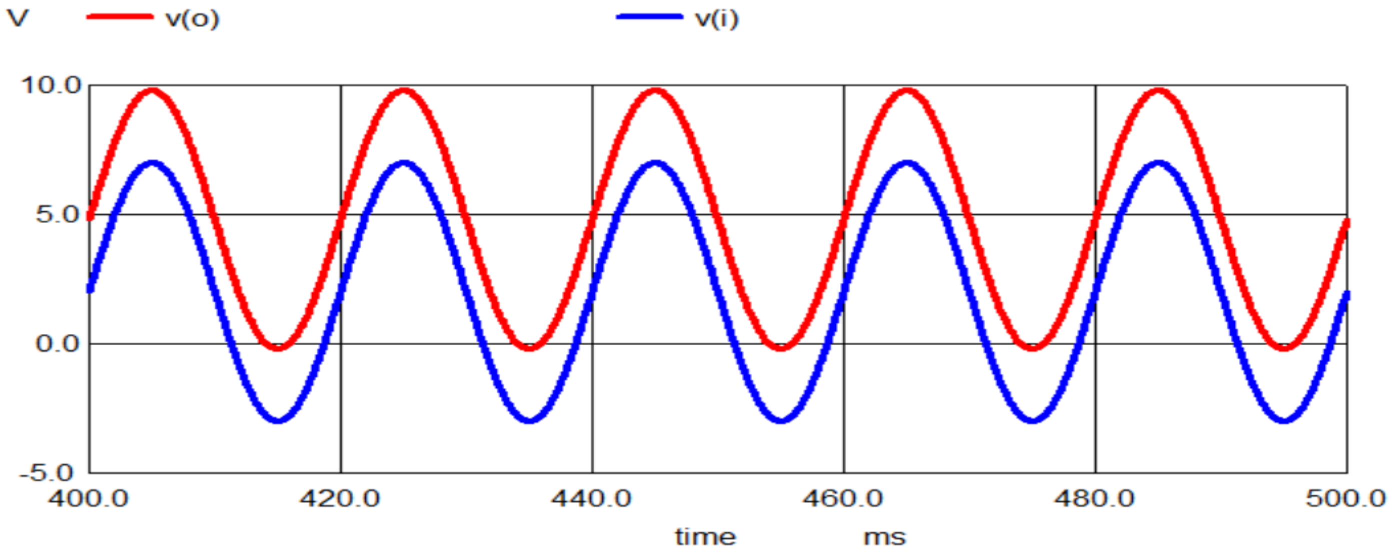


Example 1: Input v_i: sine wave with 0-V offset, peak = 5 V, valley = −5 V. Valley is clamped to 0 V, v_c = 5 V. Output v_o: peak = 10 V, valley = 0 V.

- As D is connected across the output with the polarity shown, it prevents the output voltage from going below 0 V by conducting and charging C. Under steady state operation, no current flows through the diode. This connection does not affect the positive excursion of v_0. Thus the valley of the waveform is clamped to 0 V independent of the waveshape.



- The output waveform has a finite average value or DC component, which is unrelated to the average value of the input waveform.
- The circuit becomes a peak clamping circuit by reversing the diode polarity.



Example 2: Input v_i: sine wave with 2-V offset, peak = 7 V, valley = −3 V. Valley is clamped to 0 V, v_c = 3 V. Output v_o: peak = 10 V, valley = 0 V.

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