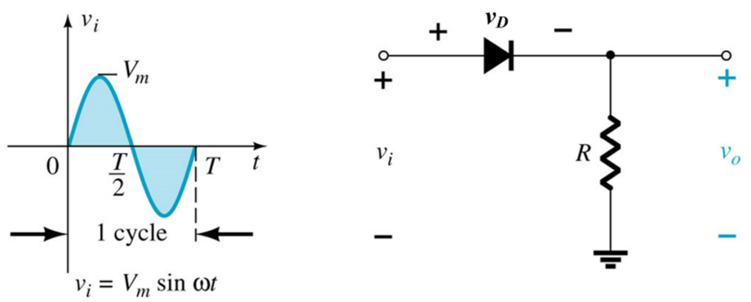
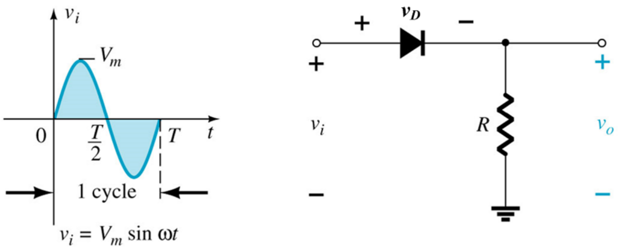
Contents

Clippers

- Clipper diode circuits have the ability to *clip* off a portion of the input signal without distorting the remaining part of the alternating waveform.
- Depending on the orientation of the diode, the positive or negative region of the input signal is *clipped* off.
- There are two general categories of clippers: **series** and **parallel**. The series configuration is defined as one where the diode is in series with the load as shown below, while the parallel variety has the diode in a branch parallel to the load.





- Let us write down the KVL equation for the circuit above

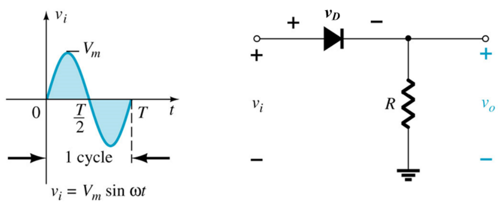
$$v_i - v_D - i_D R = 0 \quad \Rightarrow \quad v_D = v_i - i_D R$$

As $v_D|_{i_D=0} = v_i$, we have

$$\text{Diode state} = \begin{cases} ON, & \text{if } v_i \geq V_{D(ON)} \\ OFF, & \text{if } v_i < V_{D(ON)} \end{cases}$$

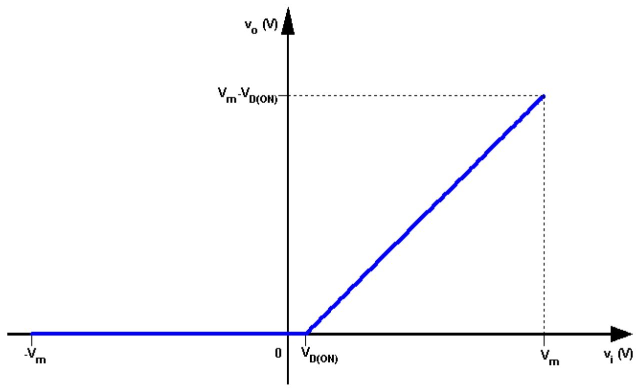
As the **output** v_o is across the resistor R, i.e., $v_o = i_D R = v_i - v_D$, we have

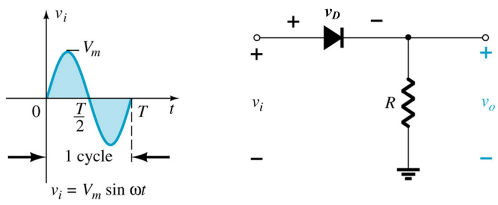
$$\boxed{v_o = \begin{cases} v_i - V_{D(ON)}, & \text{if } v_i \geq V_{D(ON)} \\ 0, & \text{if } v_i < V_{D(ON)} \end{cases}}$$



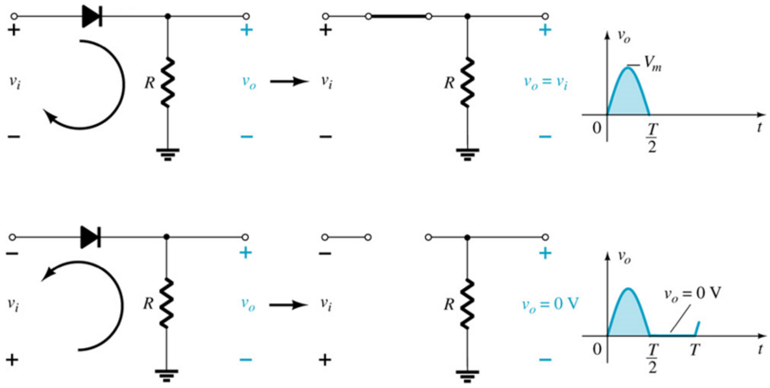
$$v_o = \begin{cases} v_i - V_{D(ON)}, & \text{if } v_i \geq V_{D(ON)} \\ 0, & \text{if } v_i < V_{D(ON)} \end{cases}$$

- Let us plot the equation above, as a **voltage transfer characteristics** (VTC) curve, i.e., output versus input plot, in order to understand the clipper behaviour visually, as shown below.



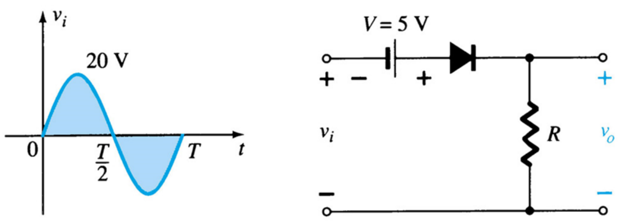


- Let us analyse the operation of the series clipper circuit above for a sinusoidal input, using the **ideal diode** model, i.e., $V_{D(ON)} = 0$.



As we see from the figures above, negative half-cycle portion of the signal is clipped off while the positive half-cycle portion remains intact.

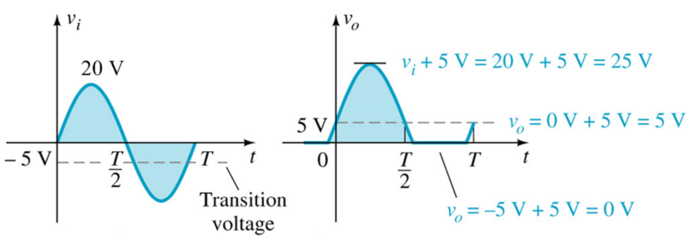
Example 1: By adding a DC source to the circuit as shown, the voltage required to forward bias the diode can be changed.



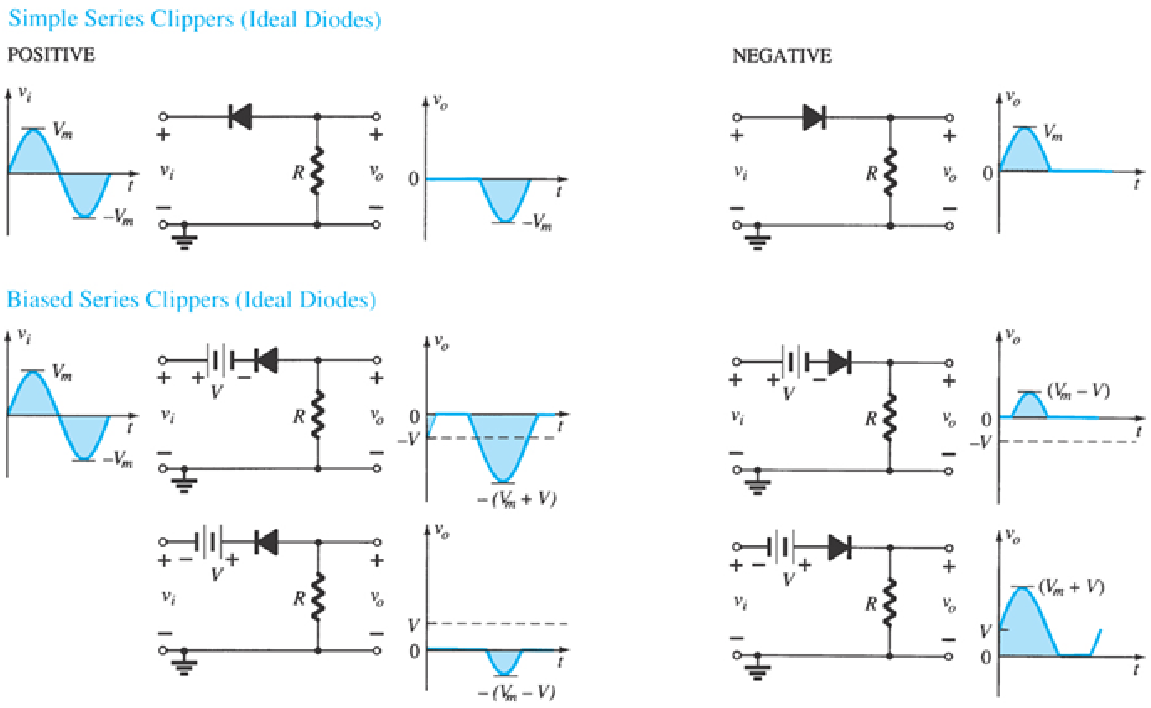
Consequently, the output will be given by

$$v_o = \begin{cases} v_i + 5\,\text{V} - V_{D(ON)}, & \text{if } v_i \geq V_{D(ON)} - 5\,\text{V} \\ 0, & \text{if } v_i < V_{D(ON)} - 5\,\text{V} \end{cases}$$

Let us sketch the output of the series clipper circuit above for a sinusoidal input, using the **ideal diode** model, as shown below.

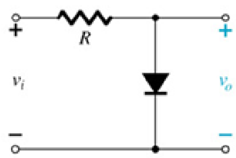


Example 2: Various series clipper examples are shown below.



Parallel Clippers

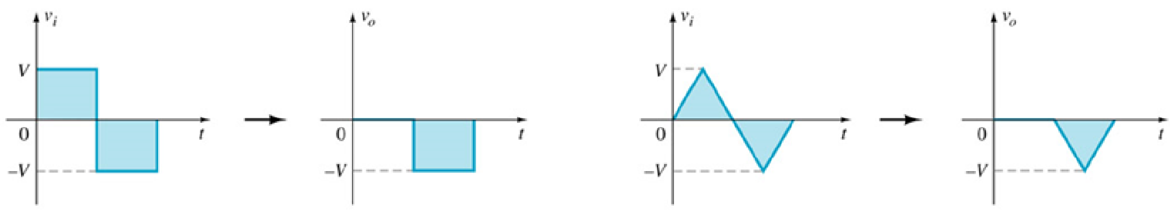
By taking the output across the diode shown below, the output equals to the input voltage when the diode is not conducting.



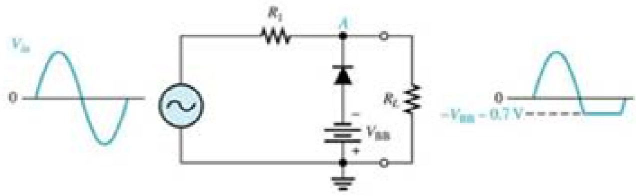
Hence, the output for this circuit will be given by

$$v_o = \begin{cases} V_{D(ON)}, & \text{if } v_i \geq V_{D(ON)} \\ v_i, & \text{if } v_i < V_{D(ON)} \end{cases}$$

Example input and output waveforms of the parallel clipper circuit above for the **ideal diode** model are shown below.



Example 3: A DC source can also be added to change the diode's required forward bias voltage, as shown



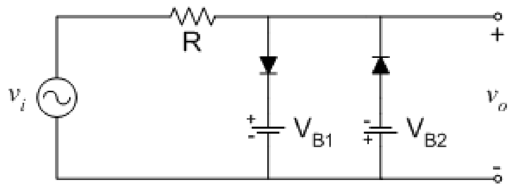
Consequently, the output will be given by

$$v_o = \begin{cases} -V_{D(ON)} - V_{BB}, & \text{if } v_i \le -V_{D(ON)} - V_{BB} \\ v_i, & \text{if } v_i > V_{D(ON)} \end{cases}$$

Homework 1: Draw the VTC diagram of the parallel clipper circuit above.

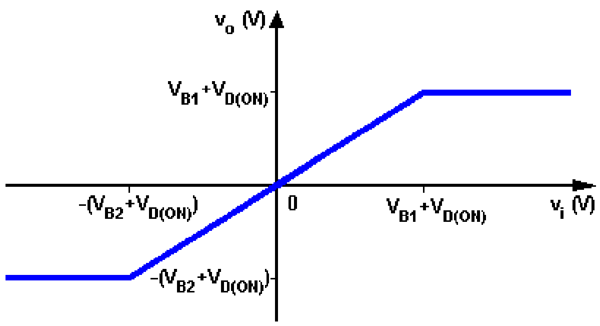
Homework 2: Draw the output waveform and the VTC diagram when the diode is reversed.

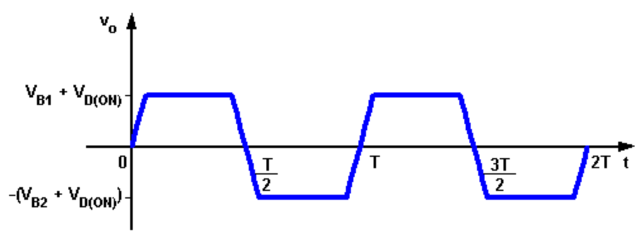
Example 4: For the circuit shown below, find the output for a sinusoidal input $v_i(t) = V_m \sin(2\pi t/T)$ where $(V_{B1}, V_{B2}) < V_m$ and draw the VTC diagram.



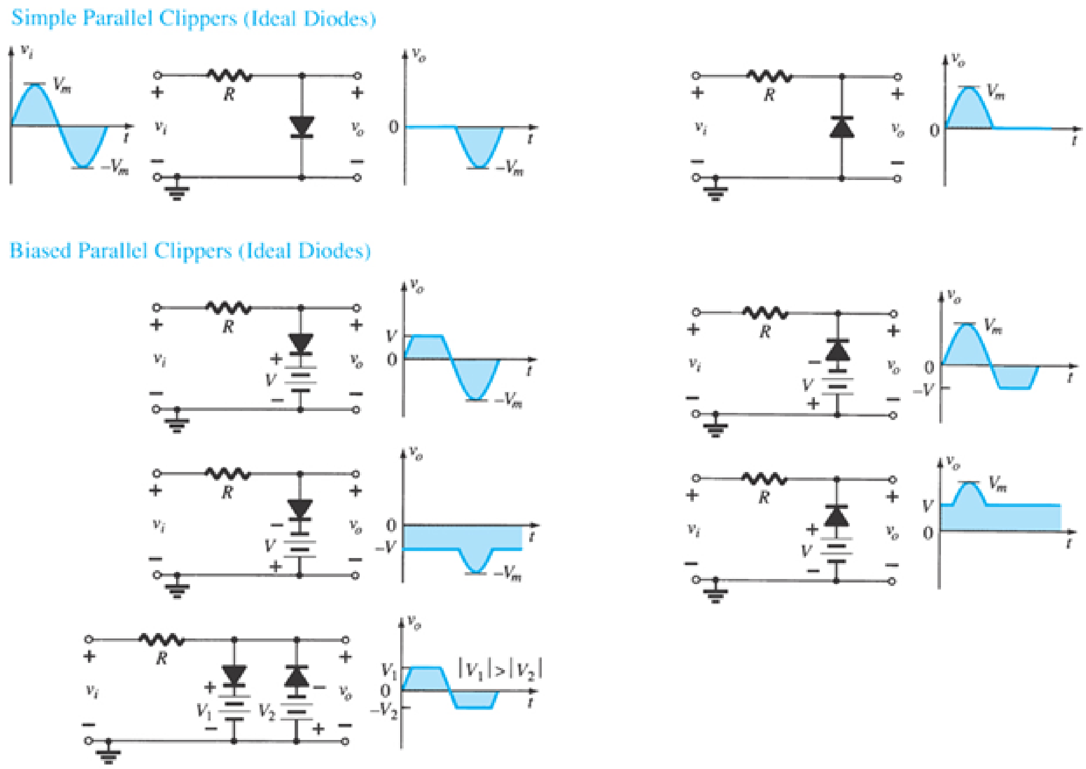
Consequently, the output is given below and also shown in the figures below

$$v_o = \begin{cases} V_{D(ON)} + V_{B1}, & \text{if } v_i \ge V_{D(ON)} + V_{B1}, \\ -V_{D(ON)} - V_{B2}, & \text{if } v_i \le -V_{D(ON)} - V_{B2}, \\ v_i, & \text{else.} \end{cases}$$



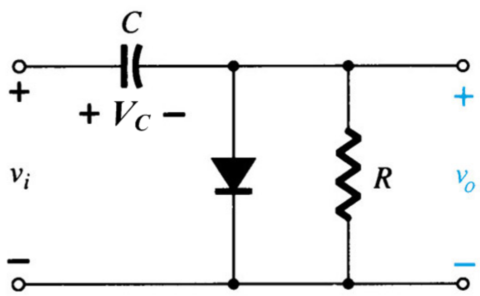


Example 5: Various parallel clipper examples are shown below.



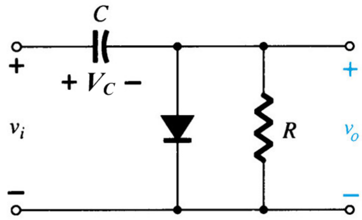
Clampers

Clamper circuits *clamp* a signal to different DC levels. The circuit must have a capacitor, a diode, and a resistive element as shown below, but it can also employ an independent DC supply to introduce an additional shift.



Throughout the analysis, we will assume that for all practical purposes the **capacitor** will **fully discharge** in **five time constants**, i.e., $5\tau_{\text{discharge}}$, where time constant $\tau_{\text{discharge}} = RC$.

The magnitude of R and C must be chosen such that the **time constant** $\tau_{\text{discharge}} = RC$ is **large enough** to ensure that the voltage across the **capacitor does not discharge** significantly during the interval the **diode** is **nonconducting**.



For the circuit above, the diode state is given by

$$\text{Diode state} = \begin{cases} ON, & \text{if } v_i \geq V_{D(ON)} + V_C \\ OFF, & \text{if } v_i < V_{D(ON)} + V_C \end{cases}$$

where V_C is the voltage across the capacitor C.

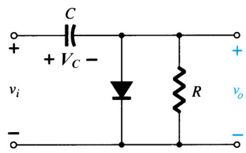
The clamper output is given by

$$v_o = v_i - V_C.$$

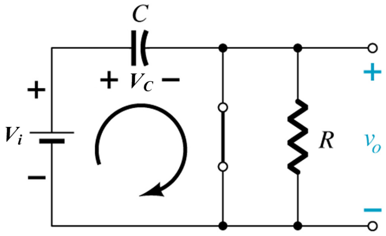
- Consequently, when the capacitor is charged at the maximum voltage, i.e., $V_C = V_m - V_{D(ON)}$ and diode is OFF, the clamper output will be

$$v_o = v_i - (V_m - V_D(ON)).$$

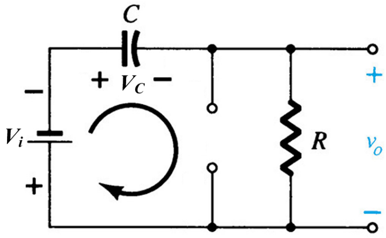
IMPORTANT: The clamper **shifts** the signal **in the direction of the diode arrowhead** by an amount of $(V_m - V_{D(ON)})$.

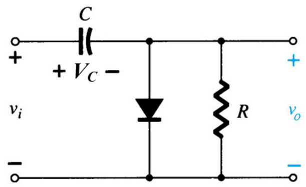


- Let us generate steps for the clamper operation for the circuit above, assuming capacitor is fully discharged initially, i.e., at $t = 0$, using the **ideal diode** model.
  1. The diode will be ON in the **first** positive half cycle as $V_C = 0$ and the capacitor will charge up very quickly to the peak value V_m with a time constant $\tau_{charge} = Cr_{av} \cong 0$ where $r_{av} \cong 0\,\Omega$ is the internal resistance of the diode as shown below.



  2. Once the capacitor is charged, i.e., $V_C = V_m$. then the diode turns OFF, as shown below.





3. Capacitor will discharge until the input waveform gets larger than the capacitor voltage, i.e., $v_i(t) > v_C(t)$. Thus, the discharging period $(\frac{T}{2})$ must be much smaller than the fully discharge constant $5\tau_{\text{discharge}}$ in order to keep the voltage across the capacitor almost constant at $V_C \cong V_m$, i.e.,

$$5\tau_{\text{discharge}} \gg \frac{T}{2}$$

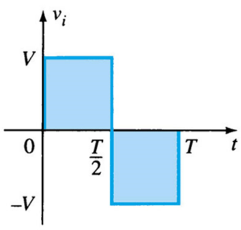
So, if take $\left(5\tau_{\text{discharge}} \geq 50\,\frac{T}{2}\right)$, then we obtain the following condition for the clamping operation

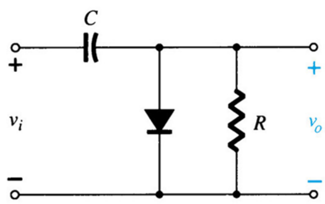
$$\boxed{\tau_{\text{discharge}} \geq 5T}$$

where T is the period of the input signal v_i.

- **For a clamping operation, selected capacitor C and resistor R values should satisfy the discharge condition above.**
- **IMPORTANT:** If it is not explicitly stated we are going to assume that **capacitor** is **already charged**, e.g., $V_C = V_m - V_{D(ON)}$.

Example 6: Consider the clamping circuit below and plot the output waveform. Assume the diode is **ideal**.

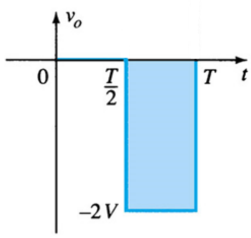




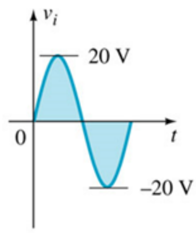
Solution: As this is a clamping circuit, i.e., $\tau_{\text{discharge}} \leq 5T$, we obtain the following output

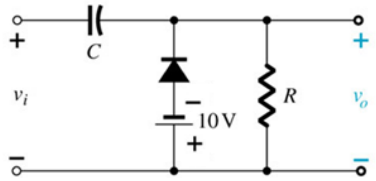
$$v_o = v_i - V + V_{D(ON)}$$

where $V_{D(ON)} = 0\,\text{V}$. The resulting waveform is shown below.



Example 7: Consider the clamping circuit below and plot the output waveform. Assume the diode is **ideal**.

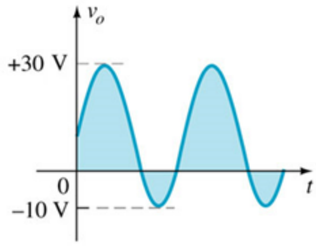




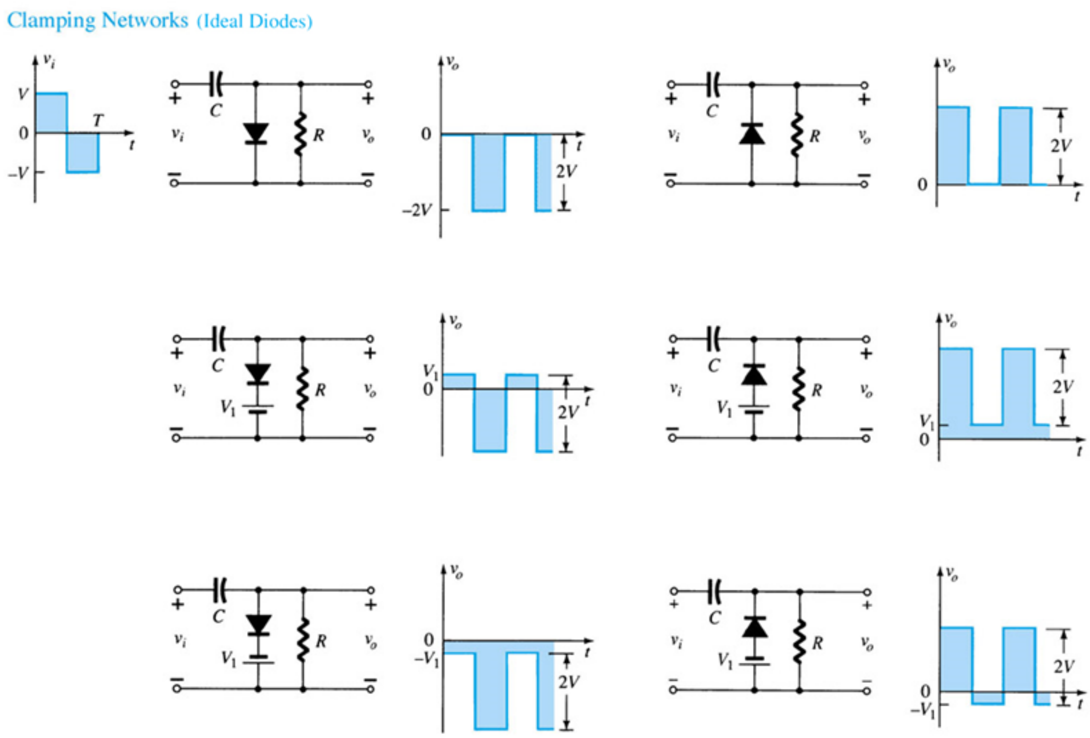
Solution: Assuming the capacitor is already charged at $V_C = -V_m + V_{D(ON)} + V_{BB} = -20 + 0 + 10 = -10\,\text{V}$, we obtain the following output

$$v_o = v_i - (-V_m + V_{D(ON)} + V_{BB}) = v_i + V_m - V_{D(ON)} - V_{BB} = v_i + 20 - 0 - 10$$
$$= v_i + 10\,\text{V}.$$

The resulting waveform is shown below.

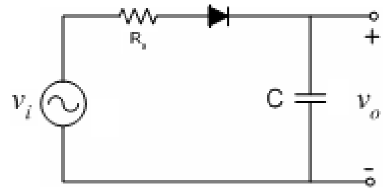


Example 8: Various clamper examples are shown below.

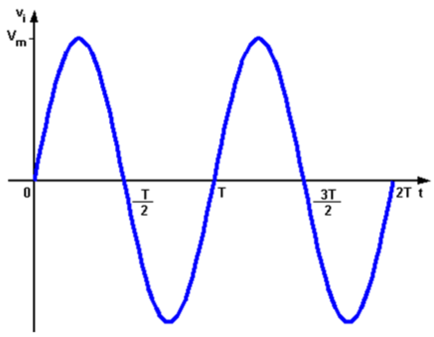


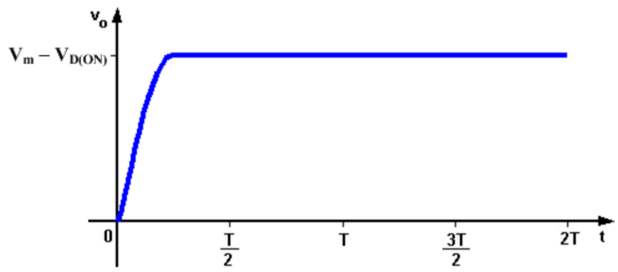
Peak Rectifier

Once we consider a clamper circuit and take the output over the capacitor instead of the diode, we obtain the **peak rectifier** circuit shown below producing a DC output at peak value of the input signal.



Corresponding input and output are also shown the two figures below. The capacitor is charged to the maximum value $(V_m - V_{D(ON)})$ in the first positive half cycle (i.e., between 0 and $T/4$), then the diode turns OFF and capacitor cannot discharge retaining the charged value. This value is equal to the **peak value** V_m for the **ideal diode**.





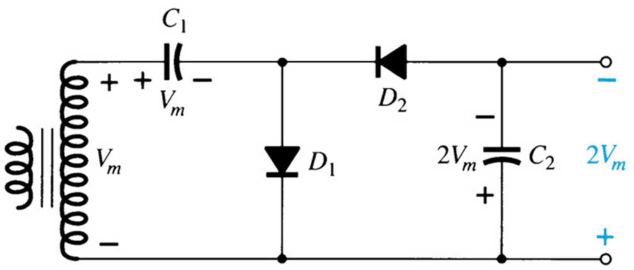
- When a load R_L is connected, the discharge constant $\tau_{discharge} = R_L C$ should have a very high value compared to the half period $\left(\frac{T}{2}\right)$ of the signal, otherwise ripples are observed at the output voltage, i.e., R_L should have a very large value.

- Using a combination of diodes and capacitors we can step up the output voltage of rectifier circuits. These circuits (some listed below) are called **voltage multiplier circuits**.

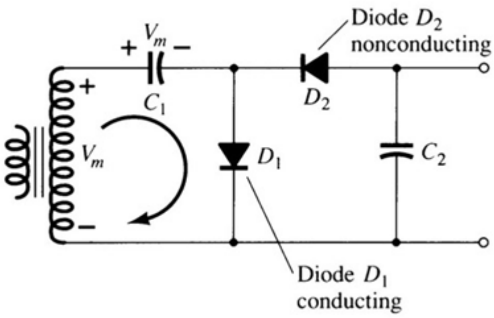
  1. Voltage Doubler
  2. Voltage Tripler
  3. Voltage Quadrupler

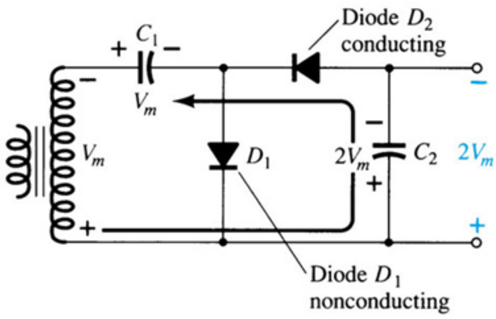
Voltage Doubler

A voltage doubler circuit is shown below.



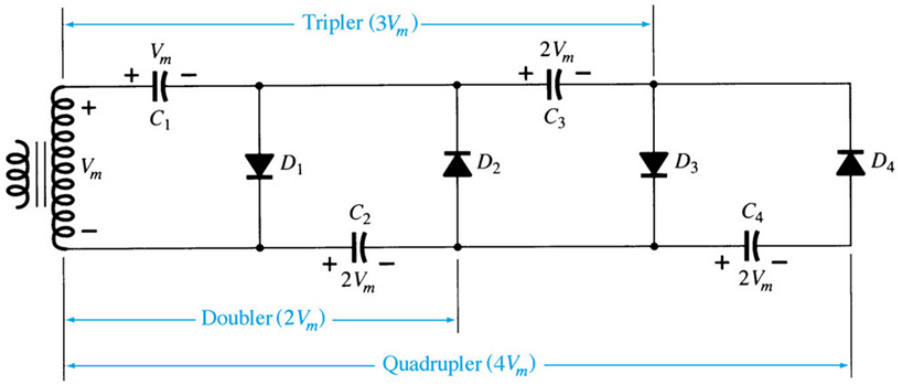
Using the **ideal diode** model, operation of the voltage doubler circuit are shown for the first positive and negative half-cycles the two figures below, respectively. After the first cycle, both diodes retain their OFF state.





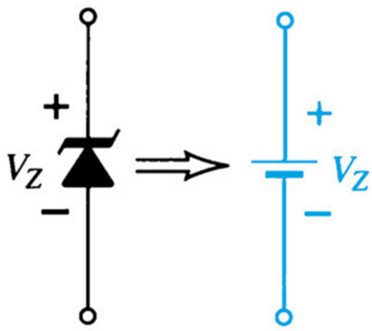
Voltage Tripler and Quadrupler

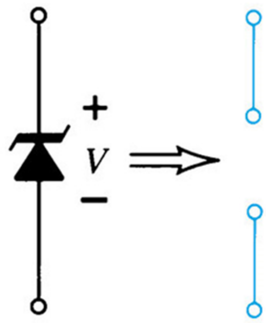
By adding more diode-capacitor networks the voltage can be increased as shown below.



Zener Diode

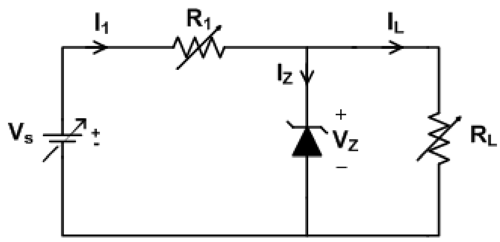
Zener diode **operates** in **reverse bias** (RB) at the Zener Voltage (V_Z). Zener diode is ON when it operates on the Zener region, i.e., $-V_D \geq V_Z$, and is OFF when $0 < -V_D < V_Z$, as shown the two figures below.





- Although Zener diode behaves like a normal diode in forward bias, Zener diode is not normally used in forward bias.
- Zener diode also needs some minimum current $I_{Z(min)}$ in order to turn ON, although voltage threshold $-V_D \geq V_Z$ is satisfied. If not given, $I_{Z(min)} = 0\,\text{A}$.
- There is also a maximum power limit $P_{Z(max)}$ for the Zener diode. Note that, maximum power limit results in a maximum current limit $I_{Z(max)}$ given by $I_{Z(max)} = \frac{P_{Z(max)}}{V_Z}$.

Zener Regulator



In a Zener regulator circuit like above, Zener diode must be always ON in order to continuously regulate the voltage over the load R_L. So, let us derive the necessary equations for the two limiting factors $I_{Z(min)}$ and $I_{Z(max)}$ using $\boxed{I_Z = I_1 - I_L}$.

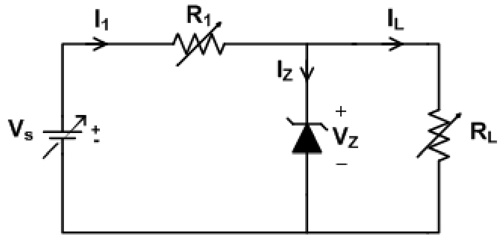
- Let us first write down the equation for $I_{Z(min)}$

$$\boxed{I_{Z(min)} = I_{1(min)} - I_{L(max)}}$$

where $I_{L(max)}$ and $I_{1(min)}$ are given by

$$I_{L(max)} = \frac{V_Z}{R_{L(min)}}$$

$$I_{1(min)} = \frac{V_{s(min)} - V_Z}{R_{1(max)}}$$



- Similarly, we can also write down the equation for $I_{Z(max)}$

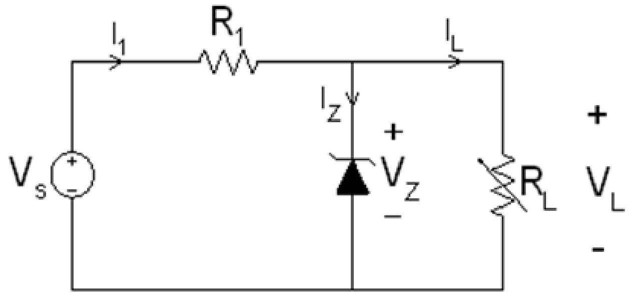
$$\boxed{I_{Z(max)} = I_{1(max)} - I_{L(min)}}$$

where $I_{L(min)}$ and $I_{1(max)}$ are given by

$$I_{L(min)} = \frac{V_Z}{R_{L(max)}}$$

$$I_{1(max)} = \frac{V_{s(max)} - V_Z}{R_{1(min)}}$$

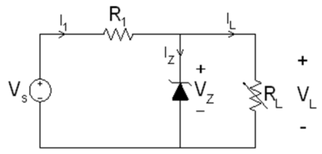
- Note that the values of V_Z, $I_{Z(min)}$ and $I_{Z(max)}$ (or $P_{Z(min)}$ and $P_{Z(max)}$) are specified in the specification sheet (or data sheet) of a Zener diode.



Example 9: (2004-2005 MI) In the figure above, V_s is an unregulated voltage that varies between $6\,\text{V}$ and $7\,\text{V}$ while the Zener diode voltage is $V_Z = 5\,\text{V}$. The load resistor R_L can have a value from $100\,\Omega$ to ∞ (i.e., open circuit). Also you can take $I_{Z(min)} \cong 0\,\text{A}$.

a) Find the **maximum** value of R_1 so that the load voltage V_L would be still kept constant at $5\,\text{V}$ **for all values** of R_L and V_s.
b) Provide a symbolic expression for the **maximum power** dissipated by the Zener diode.
c) Determine the **minimum** value of R_1 so that the power dissipated by the Zener diode does never exceeds $1\,\text{W}$ **for all values** of R_L and V_s.

Solution:



a) As $I_{Z(min)} = I_{1(min)} - I_{L(max)} = 0$, $I_{1(min)} = I_{L(max)}$, i.e.,

$$\frac{V_{s(min)} - V_Z}{R_{1(max)}} = \frac{V_Z}{R_{L(min)}}$$

$$R_{1(max)} = \frac{V_{s(min)} - V_Z}{V_Z} R_{L(min)} = \frac{6-5}{5} 100 = \underline{20\,\Omega}.$$

b) $P_{Z(max)} = V_Z I_{Z(max)}$.

c) It is given that $P_{Z(max)} = 1\,\text{W}$, so

$$I_{Z(max)} = \frac{P_{Z(max)}}{V_Z} = \frac{1}{5} = 0.2\,\text{A}$$

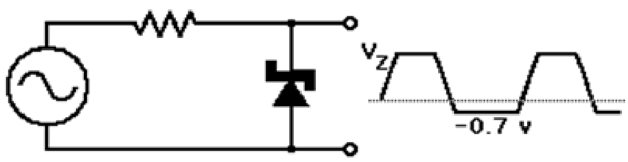
$$I_{L(min)} = \frac{V_Z}{R_{L(max)}} = \frac{5}{\infty} = 0\,\text{A}$$

$$I_{1(max)} = I_{Z(max)} + I_{L(min)} = I_{Z(max)} = 0.2\,\text{A}$$

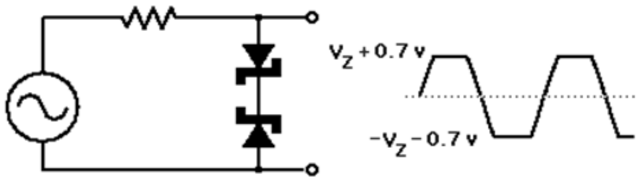
$$R_{1(min)} = \frac{V_{s(max)} - V_Z}{I_{1(max)}} = \frac{7-5}{0.2} = \underline{10\,\Omega}.$$

Other Zener Diode Regulators

- A single Zener diode can limit one side of a sinusoidal waveform to the Zener voltage while clamping the other side to near zero as shown below



- With two opposing Zeners, the waveform can be limited to the Zener voltage on both polarities as shown below.



Zener Diode Parameters

The basic parameters of a Zener diode are:

a) Obviously, the Zener voltage must be specified. The most common range of Zener voltage is 3.3 volts to 75 volts, however voltages out of this range are available.
b) A tolerance of the specified voltage must be stated. While the most popular tolerances are 5% and 10%, more precision tolerances as low as 0.05% are available. A test current ($I_{Z(test)}$) must be specified with the voltage and tolerance.
c) The power handling capability must be specified for the Zener diode. Popular power ranges are: 0.25, 0.5, 1, 5, 10, and 50 Watts.

Practical Applications of Diode Circuits

- **Rectifier Circuits**
  - Conversions of AC to DC for DC operated circuits
  - Battery Charging Circuits
- **Simple Diode Circuits**
  - Protective Circuits against
    - Overcurrent
    - Polarity Reversal
    - Currents caused by an inductive kick in a relay circuit
- **Zener Circuits**
  - Overvoltage Protection
  - Setting Reference Voltages