XMUT204 Electronic Design

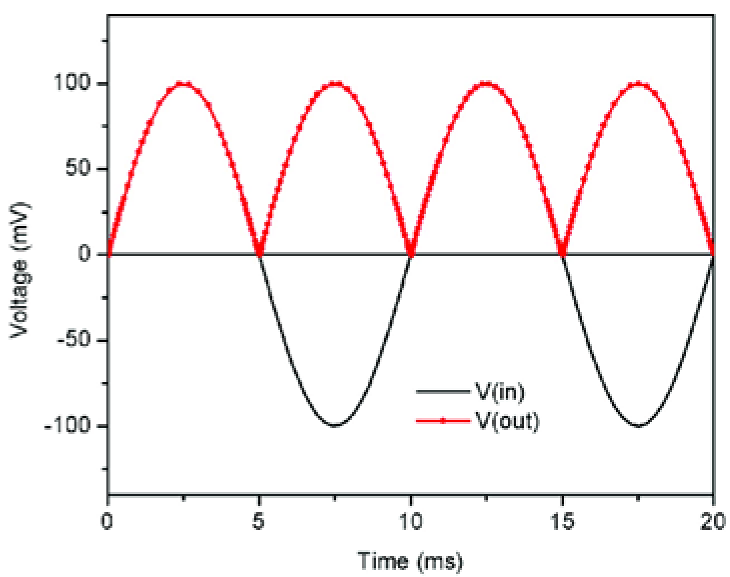
Lecture 2c - Diode Applications

Overview

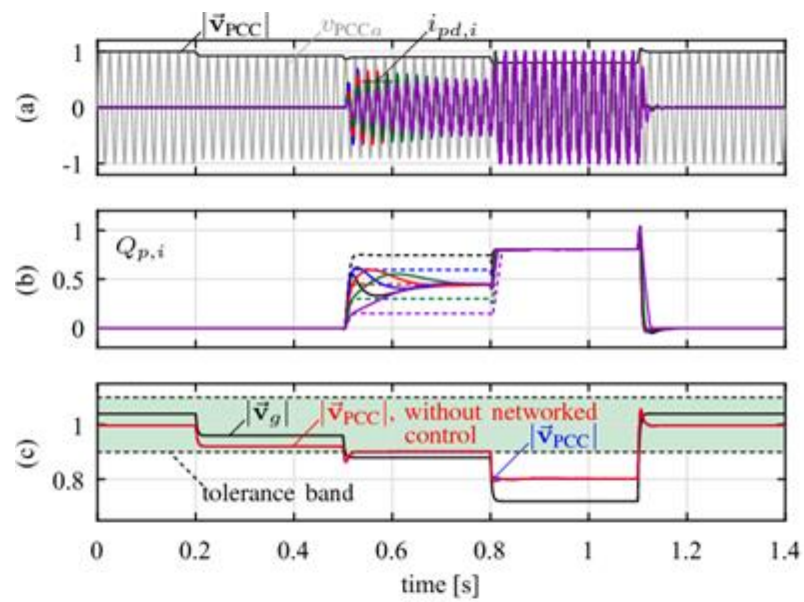
1. Rectifier Circuit.
2. Half-wave Rectifier.
3. Full-wave Rectifier (Centre Tap and Bridge Rectifiers).
4. Ripples in Rectifier Circuit.
5. Clipper Circuit.
6. Clamper Circuit.
7. Voltage Limiter Circuit.

Rectifier Circuits

- We will now look at some applications of diode circuits, especially in construction of power supplies.
- In these applications, diodes are used for voltage rectification (AC to DC conversion) and voltage regulation (maintaining constant and stable supply).



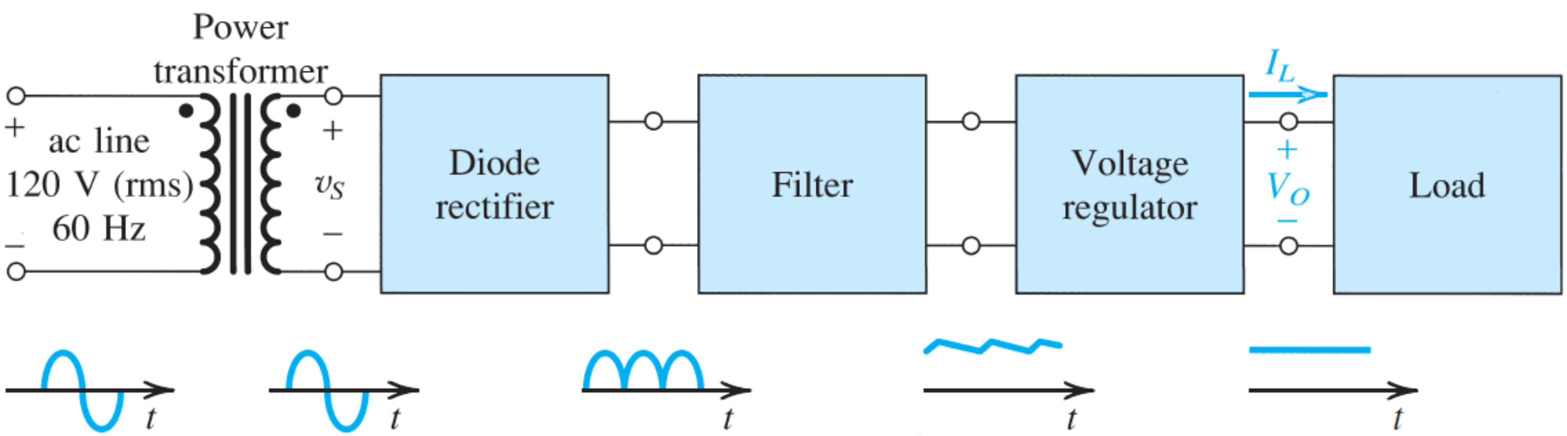
Rectification



Regulation

Rectifier Circuits

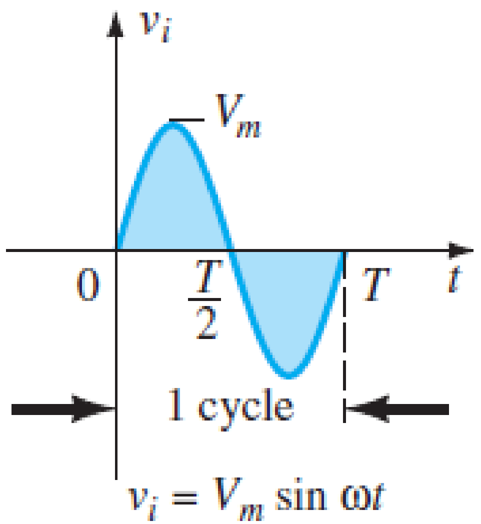
- In a given power supply circuit: diode rectifier – voltage rectification and voltage regulator – voltage regulation.



Block diagram of a typical power supply circuit

Rectifier Circuits

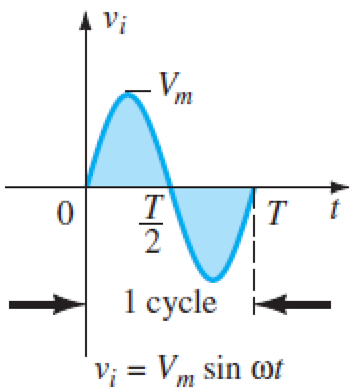
- One important application of diodes is in rectification i.e. the process of converting an AC voltage (typically sinusoidal) into a DC voltage of one polarity.
- A rectifier can be classified as a non-linear device that modifies an input voltage such that the output is greater than or less than a threshold value.

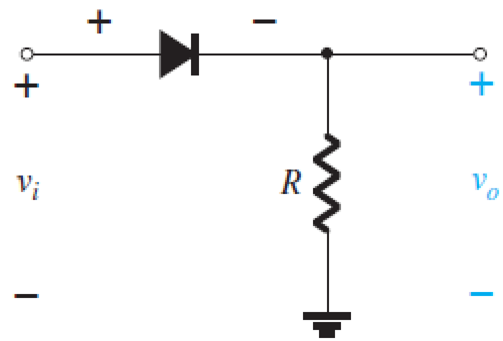


- Rectifier circuit can be classified as half-wave or full- wave rectifiers.

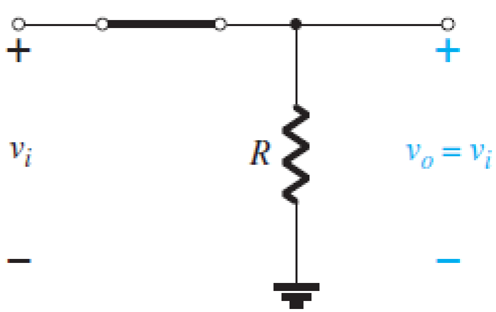
Half-wave Rectifiers - the ideal diode model

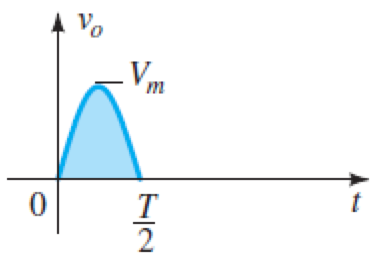
- A sinusoidal input signal v_i is used as input signal to diode (treated as an ideal diode). Output signal v_o is taken across load resistor.





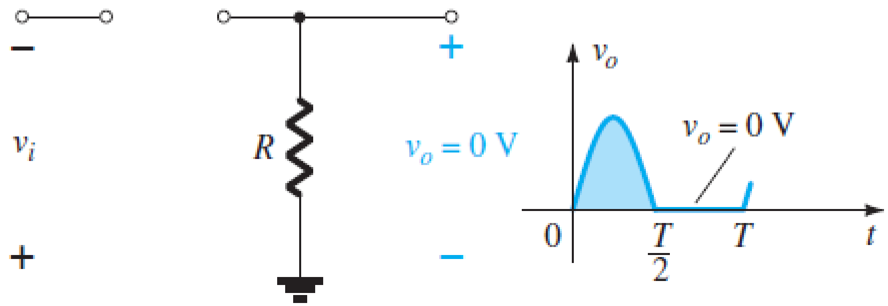
- During time t = 0 to t = $T/2$ (*positive half-cycle*) the diode is forward biased so we can model as: $V_o = V_i$.



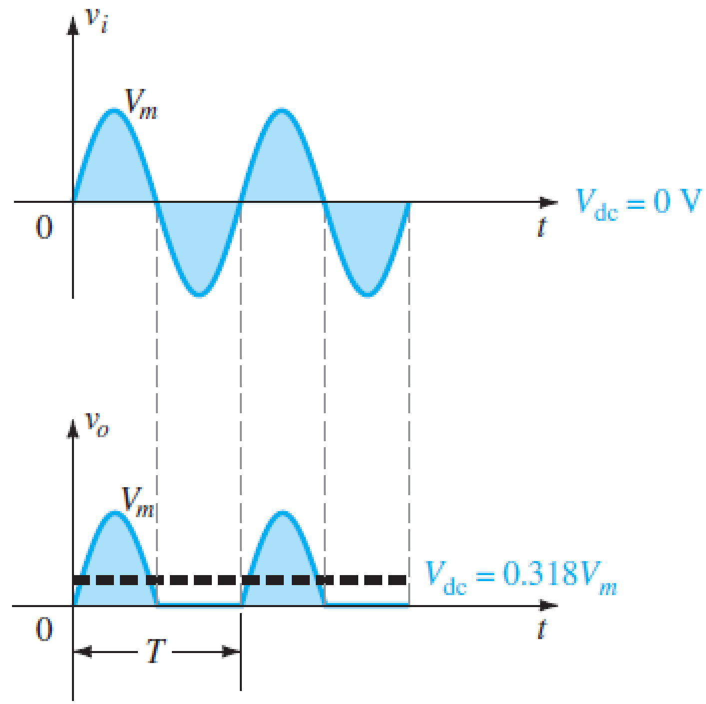


- No voltage drop across diode - Input voltage V_i will appear over R as V_o
- Positive half cycle appears unchanged at output.

- During the time $t = T/2$ to $t = T$ (*negative half cycle*) the diode is negatively biased and we can model diode as open circuit: V_o = 0 V.



  - The input voltage will then appear as $-v_d$ and no current will flow, so that output voltage, v_o = over complete half cycle.
  - Negative half cycles have been removed – signal now has an average DC value of V_{dc} = 0.318 V_m.

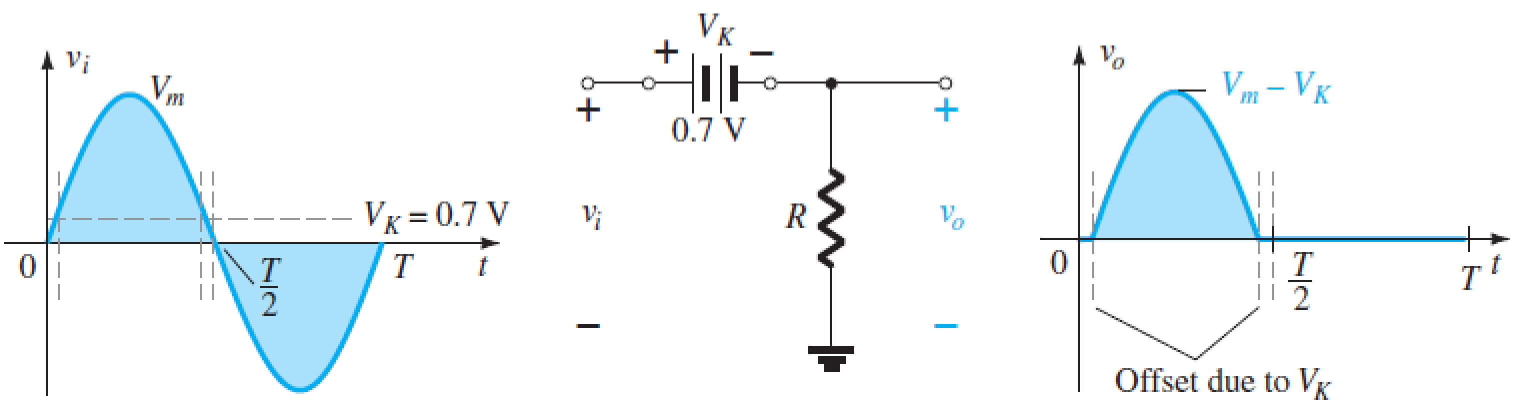


$$V_{dc(ave)} = \frac{2}{2\pi}\int_0^{\pi} V_m \sin\theta\, d\theta = \frac{V_m}{\pi}[-\cos\theta]_0^{\pi} = \frac{2V_m}{\pi} = 0.636\, V_m$$

Half-wave Rectifiers - the ideal diode + voltage source model

- We can improve the model of the system response by taking into account the approximate voltage drop over the diode.

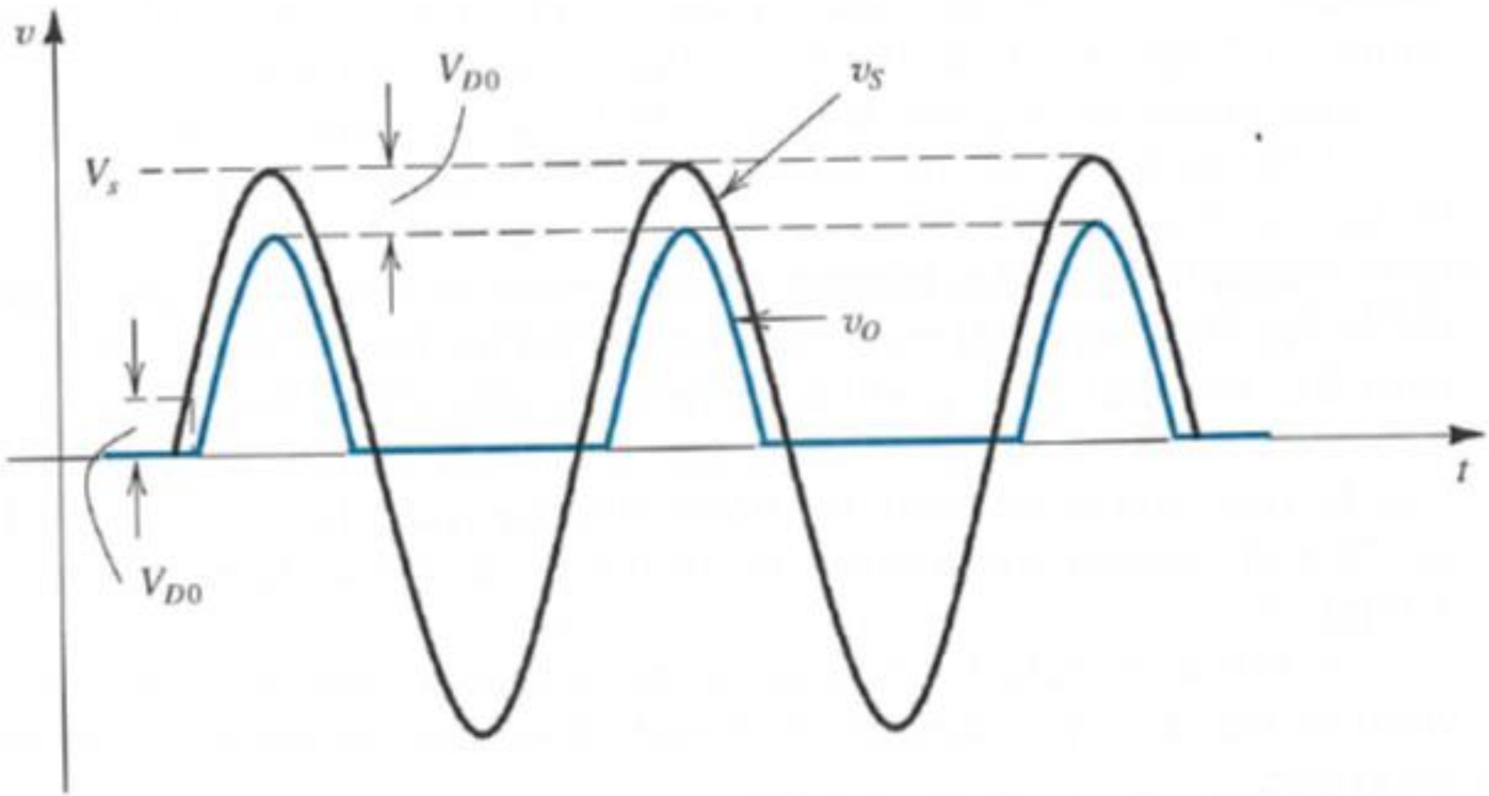
- For a Silicon diode the input signal must be at least 0.7 V before the diode will turn ON – for the V_o < 0.7 V the diode will in open circuit state.



- The DC voltage level will now reduce to:

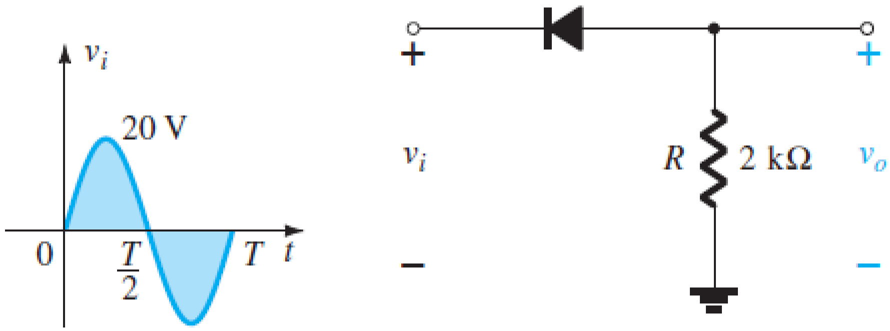
$$V_{dc} = \left(\frac{1}{\pi}\right)(V_m - V_f)$$

- More realistic representation of half-wave rectified sine wave by considering the diode as an ideal diode plus voltage source.
- This model will look like the signals observed in the output of a real life half-wave rectifier circuit.



Example for Tutorial 1 – Half-Wave Rectifier

- Consider a diode circuit as shown below, with an input voltage of 20 V and then 200 V.

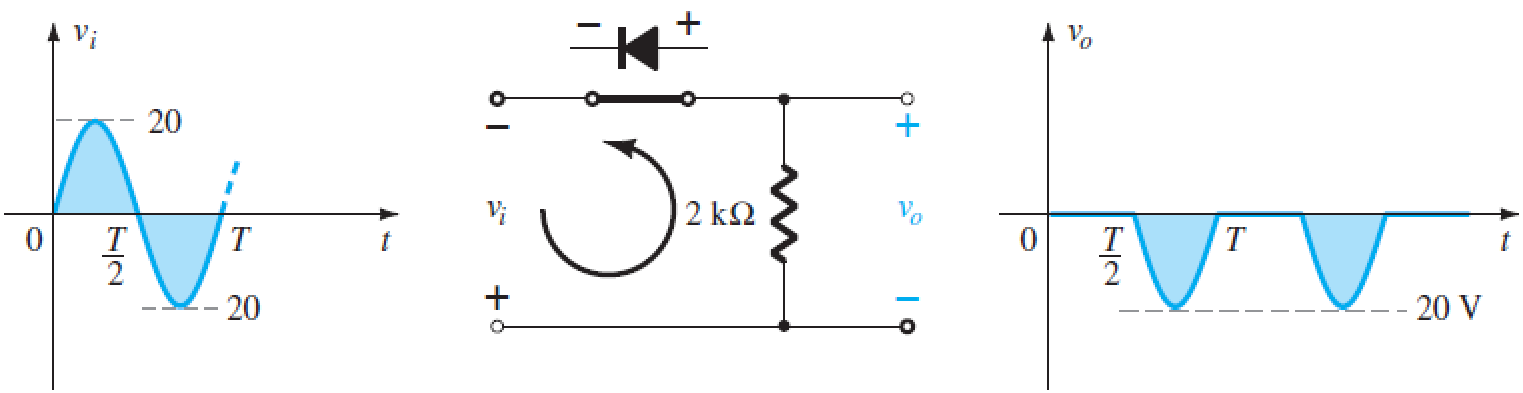


- Sketch the output V_o and determine the DC level of the output for the circuit below using both an ideal diode as well as an ideal diode + voltage source model.

Answer

- During positive half cycle of V_i the diode will be reverse biased i.e. no current will flow and zero volts will appear over the load resistor.
- During negative half cycle the diode is forward biased and current will flow i.e. only negative half cycle then permitted.
- Thus, for an ideal diode:

$$V_{dc} = -\left(\frac{1}{\pi}\right)V_i = -0.318\ (20) = -6.36\ \text{V}$$

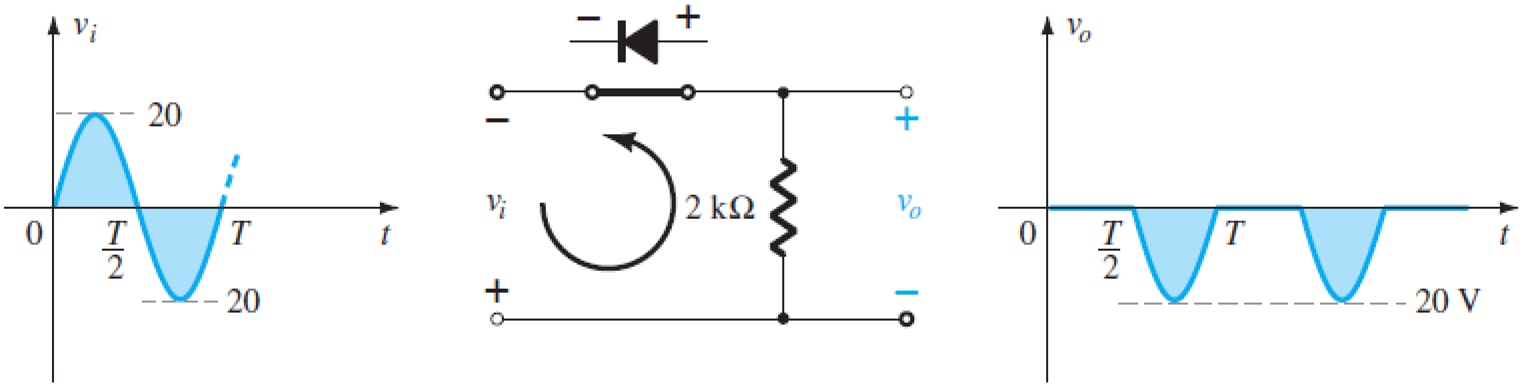


- For ideal diode + voltage source (V_d = 0.7 V for Silicon diode):

$$V_{dc} = -\left(\frac{1}{\pi}\right)(V_i - V_d) = 0.318\,(20-0.7) = -6.14\text{ V}$$

This results in a drop in dc level ~ 3.5%

- For V_i = 200 V, the output voltages are:
  - V_o = -63.6 V with ideal diode model.
  - V_o = -63.28 V for ideal diode + voltage drop model.
- This is small enough to ignore!



Diode Device Parameters for Rectifiers

Two important device parameters must be taken into account when selecting diodes for rectifiers:

- The diode current carrying capacity – the maximum current that can flow through the diode in forward bias.
- The peak inverse voltage (PIV) is the maximum voltage that can be put on the diode in reverse bias before it will go into breakdown.

For a half-cycle rectifier, we need $PIV > V_m$ where: V_m is the peak input voltage.

- Relevant circuit parameters of the rectifier circuits that typically used in the circuit analysis are circuit currents: I_m, I_{dc}, and I_{rms}, input (P_{in}) and output (P_{out}) powers, output voltage (V_{out}), and efficiency of the rectifier circuit (η).

Example for Tutorial 2 – Device and Circuit Parameters

A diode having internal resistance R_d = 10 Ω is used for half-wave rectifier circuit. If the applied voltage is $v = 50\sin(\omega t)$ and load resistance R_L = 1000 Ω. Find the following:

a. PIV of the diode. [2 marks]
b. Currents I_m, I_{dc}, and I_{rms}. [6 marks]
c. AC power input and DC power output. [4 marks]
d. DC output voltage. [2 marks]
e. Efficiency of rectification. [2 marks]

Answer

a. The PIV of the diode, $PIV > V_m$. As the maximum voltage, V_m = 50 V, then PIV > 50 V.

b. Since maximum voltage, V_m = 50 V, the maximum current of half-wave rectifier circuit is:

$$I_m = \frac{v_m}{R_d + R_L} = \frac{50}{10 + 1000} = 49.5 \text{ mA}$$

The DC current is:

$$I_{dc} = I_{avg} = \frac{I_m}{\pi} = \frac{49.5}{\pi} = 15.76 \text{ mA}$$

The RMS current is:

$$I_{rms} = \frac{I_m}{2} = \frac{49.5}{2} = 24.75 \text{ mA}$$

c. The AC power of half-wave rectifier circuit is:

$$P_{ac} = (I_{rms})^2(R_d + R_L)$$
$$= (24.75 \times 10^{-3})^2 \times (10 + 1000) = 0.618\ \text{W}$$

The DC power is:

$$P_{dc} = (I_{dc})^2(R_L) = (15.76 \times 10^{-3})^2 \times (1000) = 0.248\ \text{W}$$

d. The DC output voltage of half-wave rectifier circuit is:

$$V_{DC} = I_{dc} \times R_L = (15.76 \times 10^{-3}) \times 1000 = 15.76\ \text{V}$$

e. The efficiency (η) of half-wave rectifier circuit is:

$$\eta = \frac{P_{dc}}{P_{ac}} = \left(\frac{0.248}{0.618}\right) \times 100 = 40.12$$

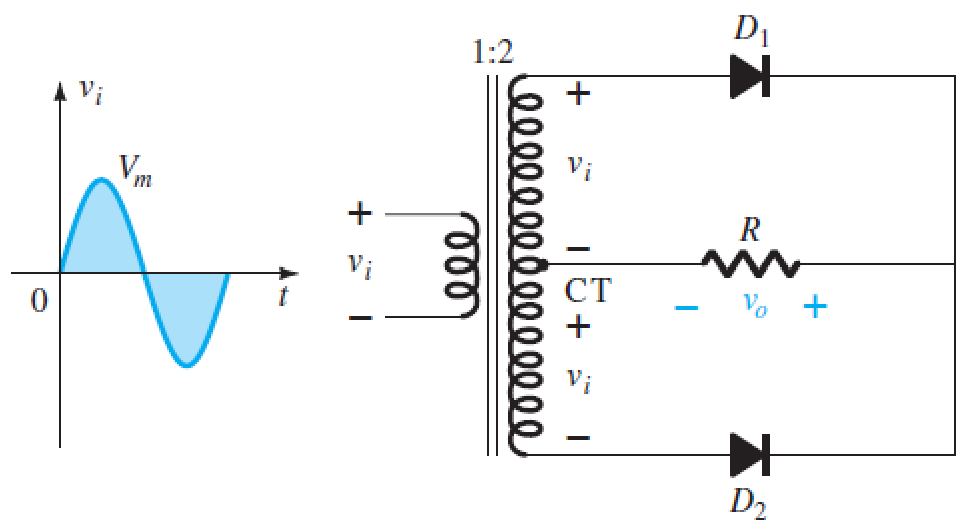
Full-wave Rectification

- DC level obtained from a sinusoidal input and a half-wave rectifier can be doubled by using a full wave rectifier.
- This can be performed using two methods:
  - Centre-tapped transformer + two diodes
  - Bridge rectifier using four diodes.

    Typically done using a diode bridge consisting of four diodes i.e. made so that two diodes contact on positive half-cycle and the other two conduct on negative half-cycle.

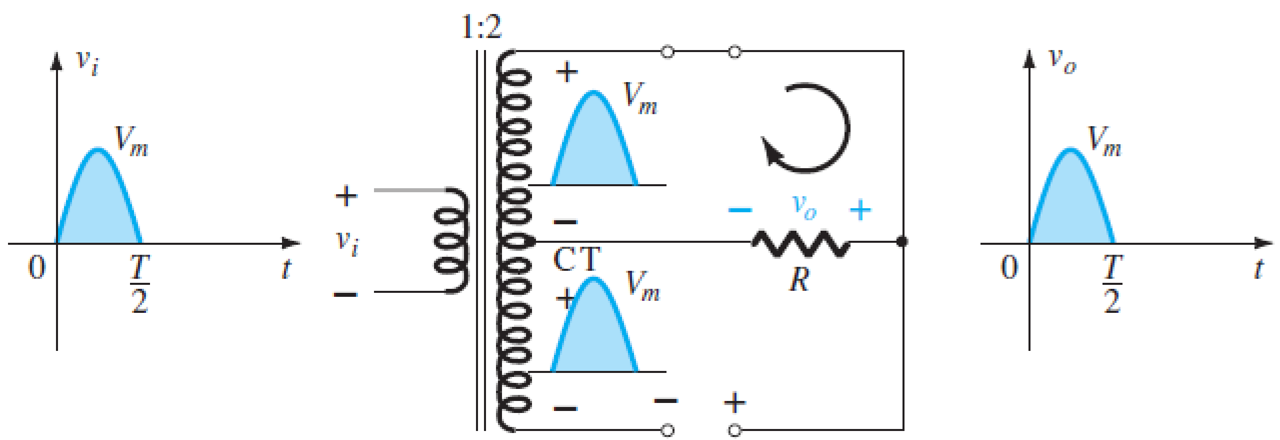
A centre-tapped transformer rectifier

- A CT transformer is like a conventional transformer, but its secondary winding is divided into two parts i.e. two individual voltages.
- For typical AC input, ordinary transformer i.e. one voltage, say 220 V. But, CT transformer i.e. two voltages each of 110 V



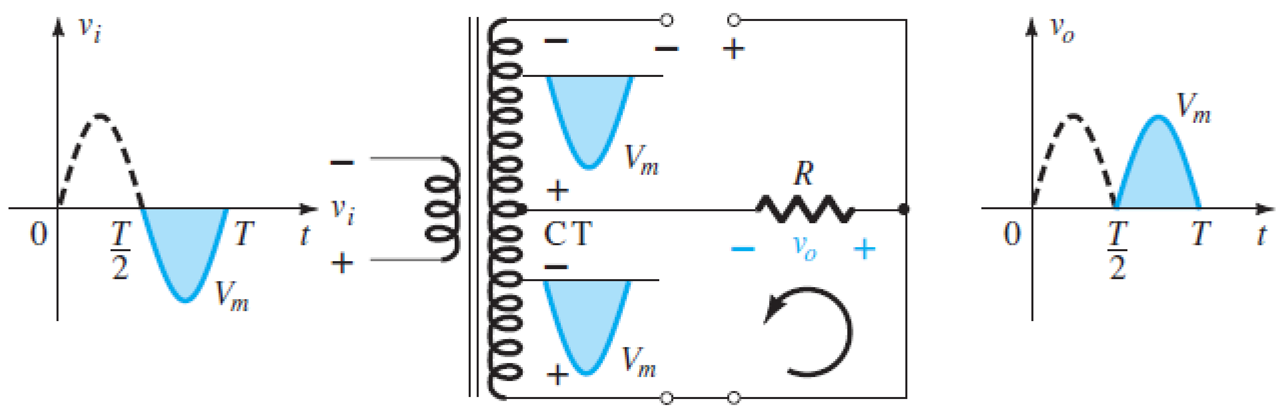
During positive half cycle of input voltage:

- Top diode in forward bias and bottom diode in reverse bias.
- Current flows through resistor as indicated.



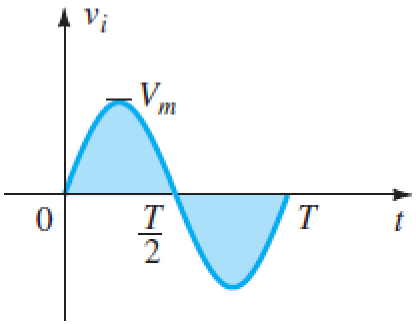
During negative half cycle of input voltage:

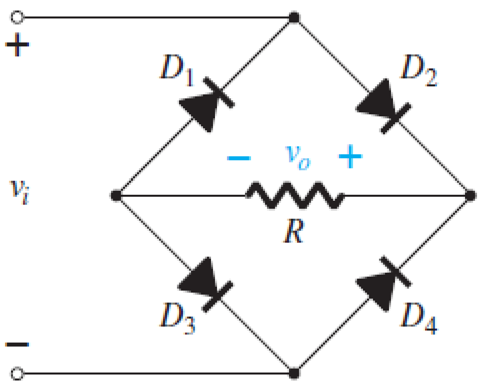
- Top diode in reverse bias and bottom diode in forward bias.
- Current flows through resistor as indicated i.e. same direction as in previous case.
- Negative input half cycle appears as a positive output half cycle.



Diode bridge network

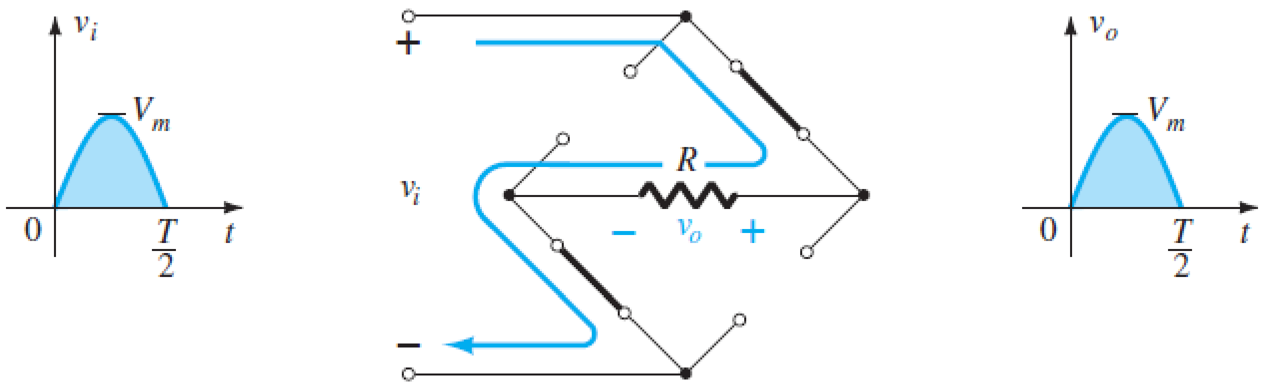
- Consists of four diodes i.e. two of the four will conduct on any half cycle of the input voltage.





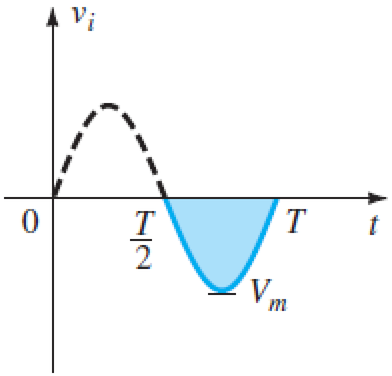
Diode bridge on “+” half cycle

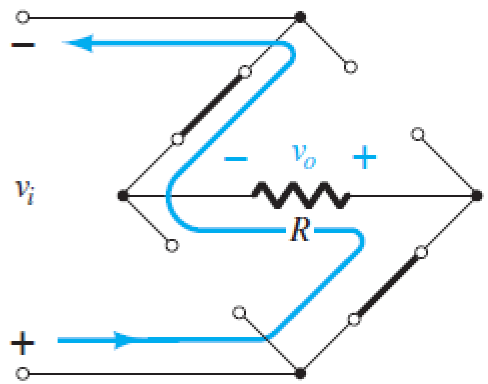
- During period t = 0 to t = $T/2$ the diodes D_2 and D_3 are on and the output voltage can be taken over the resistor with polarity as shown.

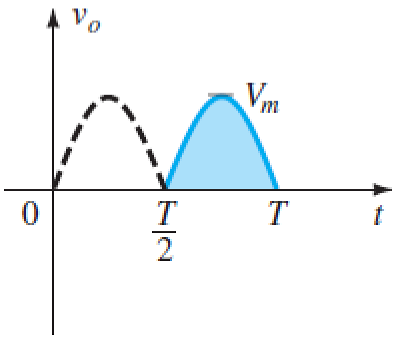


Diode bridge on "-" half cycle – t from $T/2$ to T

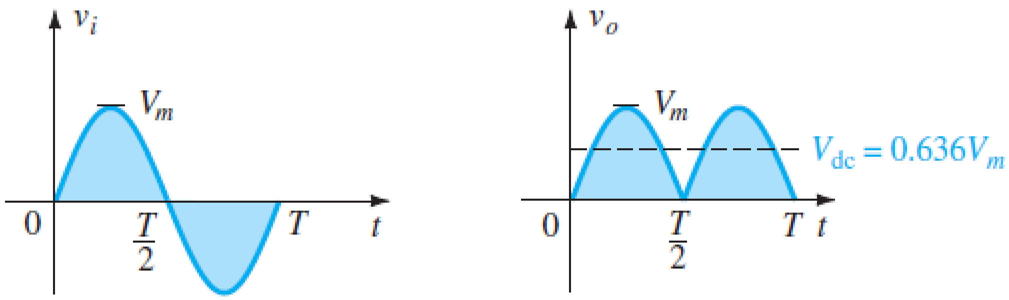
- Diodes D_1 and D_4 are now forward biased i.e. current will flow and the voltage across R will have the same polarity as in first half cycle.







- In each case (+ and – half cycles), the polarity across the resistor is then the same i.e. converted to the same polarity output voltage.



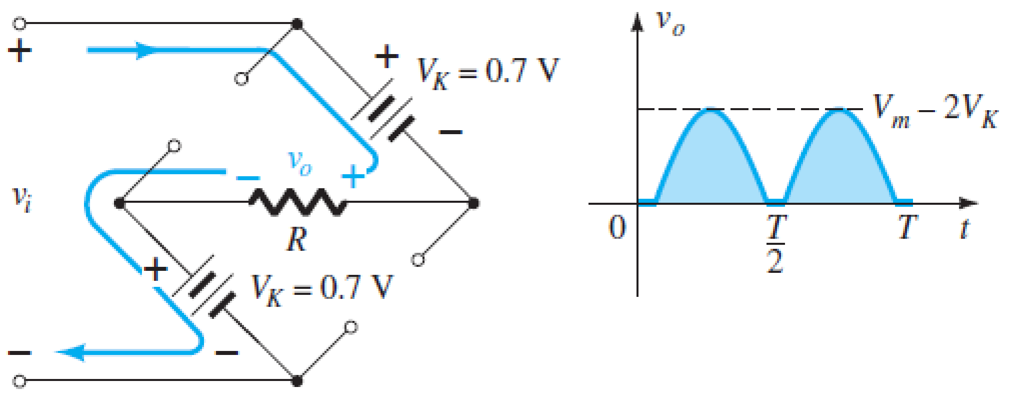
- The DC level of the signal has now been doubled from that of the half wave rectifier. For a ideal diodes:

$$V_{dc} = \left(\frac{2}{\pi}\right) V_m$$

- or when using the ideal diode + voltage source model:

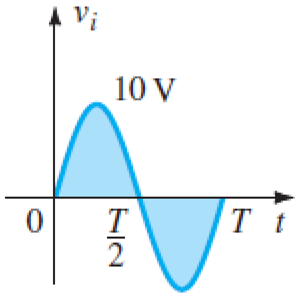
$$V_{dc} = \left(\frac{2}{\pi}\right) (V_m - 2V_B)$$

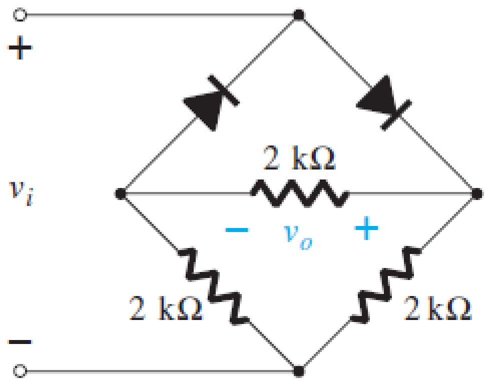
- For Silicon diodes rather than an ideal diode, there is 0.7 voltage drop across the diode.



Example for Tutorial 3 – Full-Wave Rectifier

Determine the output waveform and calculate the output DC voltage for the network circuit below.

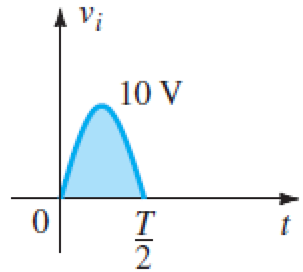


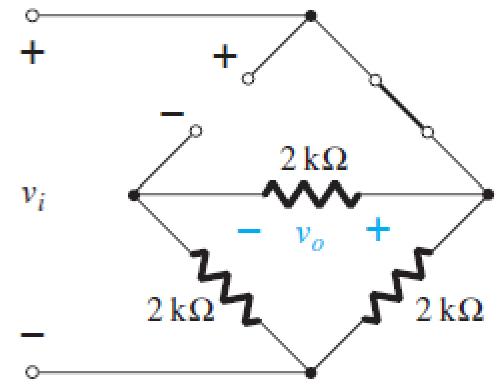


Answer

- For given bridge rectifier circuit, output voltage is:

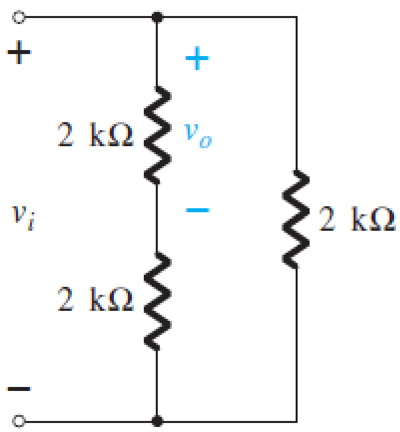
$$v_o = \frac{1}{2} v_i$$

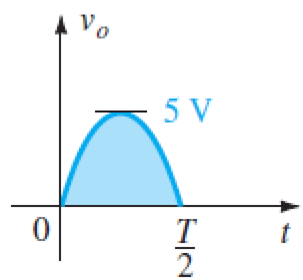


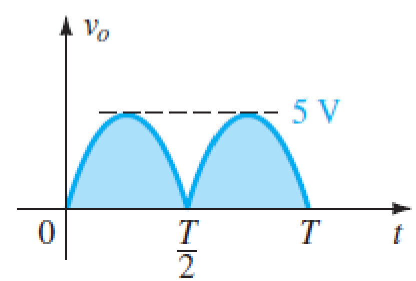


- Or

$$V_o(\text{max}) = \frac{1}{2} V_i(\text{max}) = \frac{1}{2}(10) = 5\ \text{V}$$







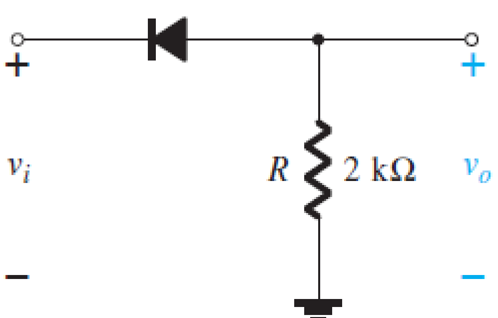
- DC level of the circuit is calculated to the following:

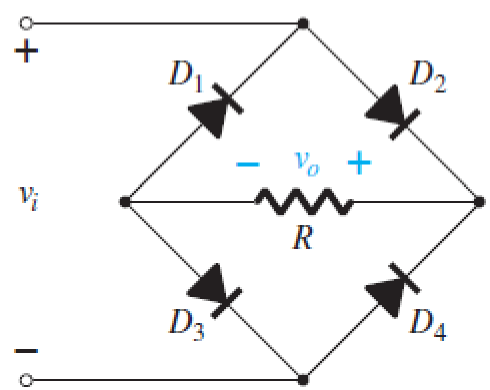
$$V_{dc} = \left(\frac{2}{\pi}\right) V_o = 0.636(5) = 3.18 \text{ V}$$

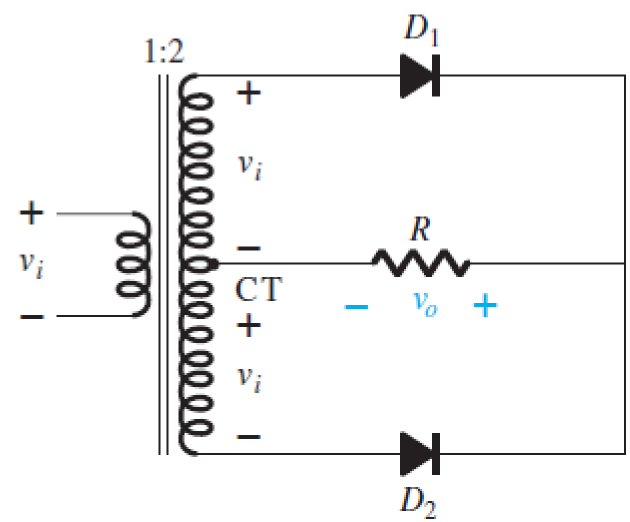
- PIV is determined from the figure below that is equal to the maximum voltage across R, which is 5 V.

Ripples in Rectifier Circuit

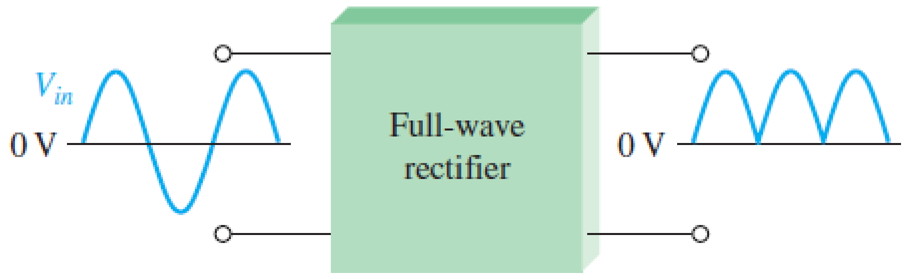
- In rectifier circuit, power line voltage must be converted to an approximately constant dc voltage.
- The 50 Hz pulsating dc output of a half-wave rectifier or 100 Hz pulsating output of a full-wave rectifier must be filtered to reduce the large voltage variations.
- Small amount of fluctuation in the filter output voltage is called ripple.



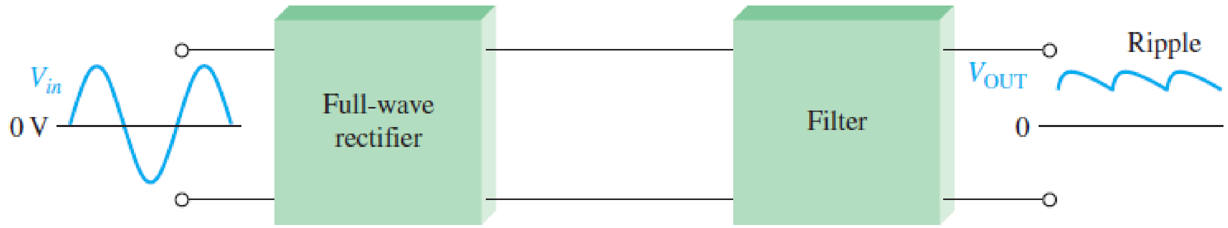




Ripples in Rectifier Circuit

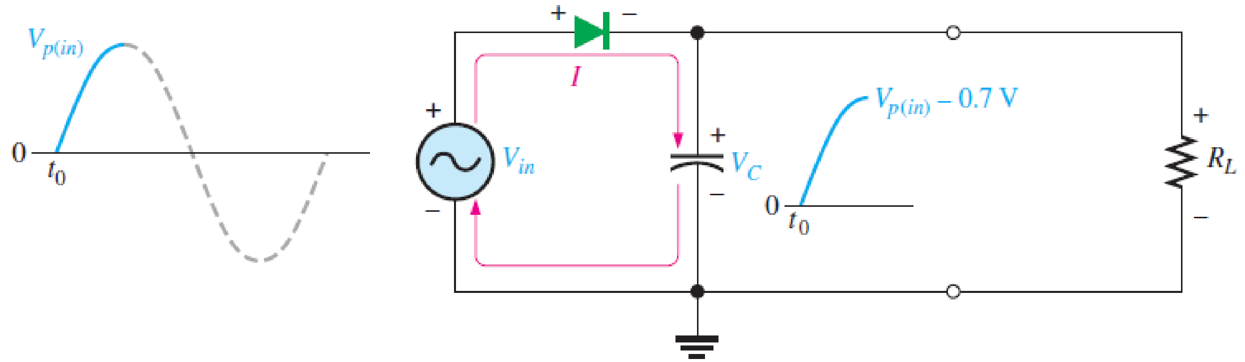


(a) Rectifier without a filter

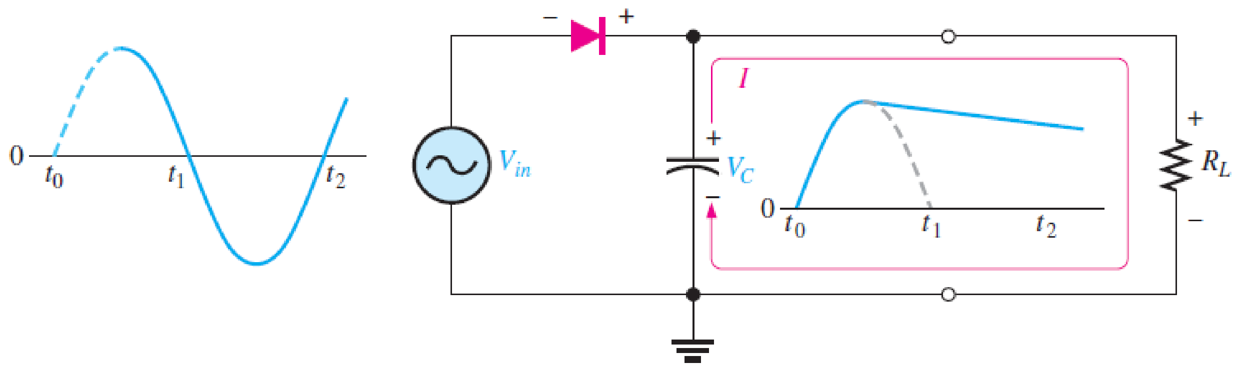


(b) Rectifier with a filter (output ripple is exaggerated)

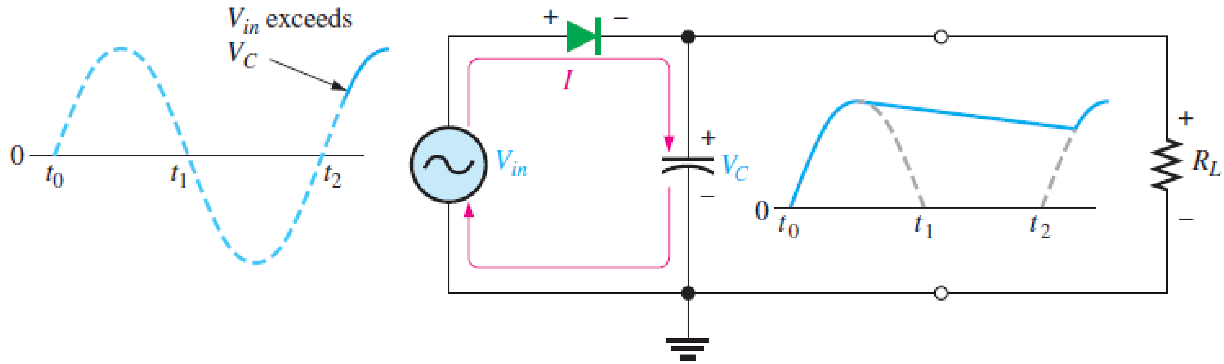
Capacitor Input Filter in Rectifier Circuit



(a) Initial charging of the capacitor (diode is forward-biased) happens only once when power is turned on.



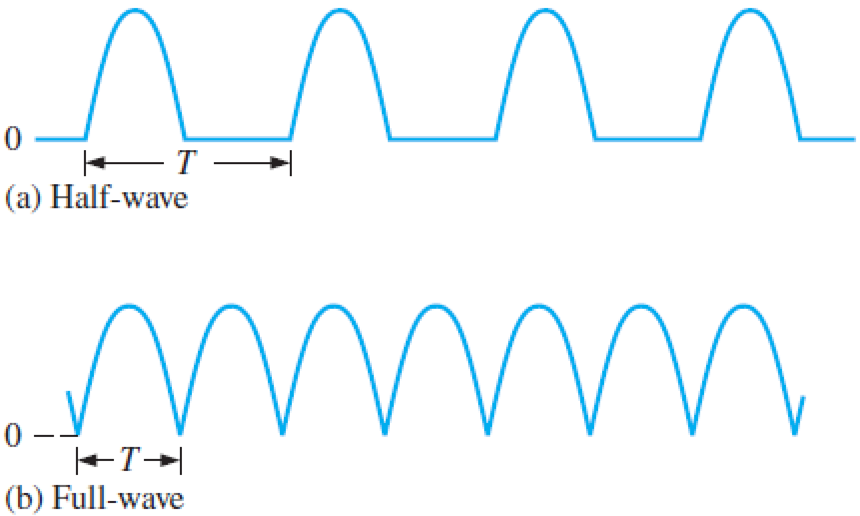
(b) The capacitor discharges through R_L after peak of positive alternation when the diode is reverse-biased. This discharging occurs during the portion of the input voltage indicated by the solid dark blue curve.



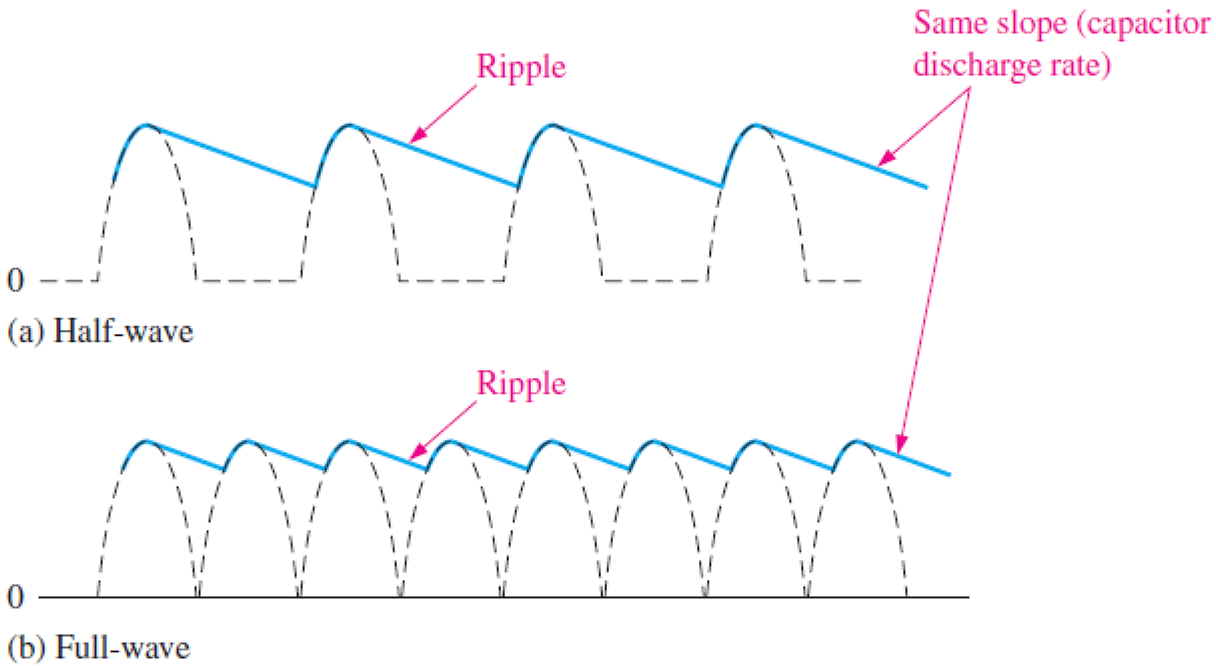
(c) The capacitor charges back to peak of input when the diode becomes forward-biased. This charging occurs during the portion of the input voltage indicated by the solid dark blue curve.

- A full-wave rectifier easier to filter because of the shorter time between peaks.
- When filtered, a full-wave rectified voltage has a smaller ripple than a half-wave voltage for the same load resistance and capacitor values.
- The capacitor discharges less during the shorter interval between full-wave pulses.

- Waveforms of half-wave and full-wave rectifiers



- Ripple waveforms of half-wave and full-wave rectifiers



- The period of a full-wave rectified voltage is half of a half-wave rectified voltage.
- The output frequency of a full-wave rectifier is twice of a half-wave rectifier.
- For a full-wave rectifier, peak primary voltage is:

$$V_{p(pri)} = \sqrt{2}\, V_{rms}$$

- Where n is the transformer turns ratio, the peak secondary voltage is:

$$V_{p(sec)} = nV_{p(pri)}$$

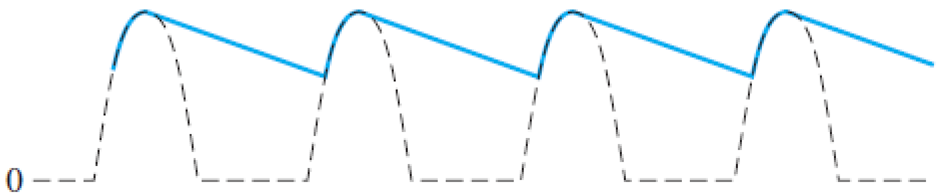
- Unfiltered peak full-wave rectified voltage is:

$$V_{p(rect)} = V_{p(sec)} - (2)(V_{BE})$$

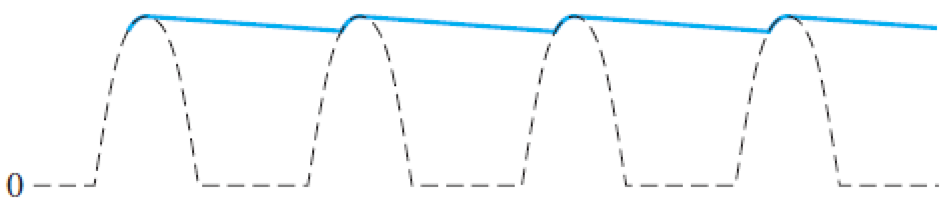
- Variable $V_{p(rect)}$ is the unfiltered peak rectified voltage.

Ripples Factor (r)

The ripple factor (r) is an indication of the effectiveness of the filter and can be used further to determine the values of the components in the rectifier circuit.



(a) Larger ripple (blue) means less effective filtering.



(b) Smaller ripple means more effective filtering. Generally, the larger the capacitor value, the smaller the ripple for the same input and load.

- For a full-wave rectifier with a capacitor-input filter, peak-to-peak ripple voltage, $V_{r(pp)}$, and the dc value of the filter output voltage, V_{DC}, are derived below.
- If the frequency of a full-wave rectified voltage is f, the approximate peak-to-peak ripple voltage at the output is:

$$V_{r(pp)} \cong \left(\frac{1}{fR_LC}\right)V_{p(rect)}$$

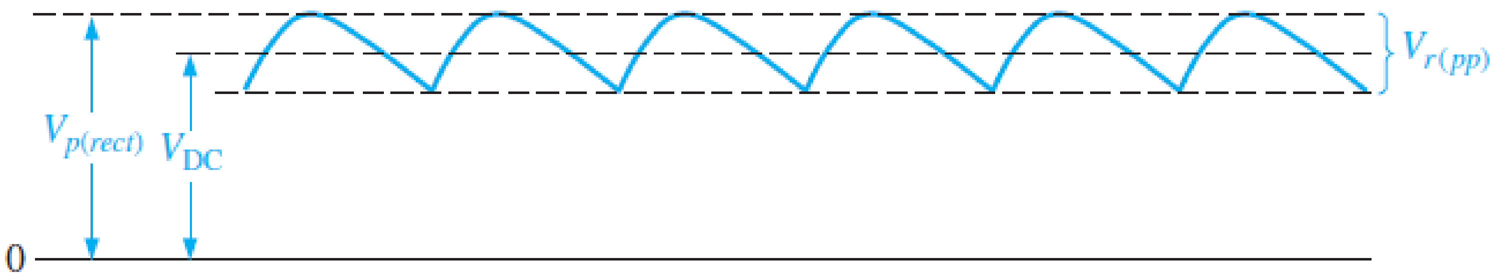
- Then, the approximate dc value of the output voltage is determined as follows:

$$V_{DC} = \left(1 - \frac{1}{2fR_LC}\right)V_{p(rect)}$$

- Thus, the ripple factor, r is:

$$r = \frac{V_{r(pp)}}{V_{DC}}$$

Where $V_{r(pp)}$ is the peak-to-peak ripple voltage and V_{DC} is the dc (average) value of the filter's output voltage.



- The lower the ripple factor, the better the filter. If R_L or C is up, the ripple voltage decreases and the dc voltage increases.
- Ripple factor can be lowered by increasing value of the filter capacitor or increasing the load resistance.

Example for Tutorial 4 – Ripples in Rectifier Circuit

For given diode rectifier circuits, perform the following tasks:

a. Define ripple factor and derive its expression from RMS and DC currents or voltages. [14 marks]
b. Calculate ripple factor of half-wave rectifier circuit and comment on the results. [8 marks]
c. Calculate ripple factor of full-wave rectifier circuit and comment on the results. [8 marks]

Answer

a. As per definition, ripple factor is the ratio of RMS of AC component to RMS of DC components in rectified output.

Ripple factor is given in terms of RMS value of AC component to RMS value of DC component.

$$\text{Ripple factor}, \gamma = \frac{\sqrt{(I_{rms})^2 - (I_{dc})^2}}{I_{dc}}$$

Or

$$\text{Ripple factor}, \gamma = \frac{\sqrt{(V_{rms})^2 - (V_{dc})^2}}{V_{dc}}$$

Knowing I_{rms} and I_{dc}, we can find the ripple factor of the rectifier.

$$I_{rms} = \sqrt{I_{dc}^2 + I_{ac}^2} \qquad \text{or} \qquad I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2}$$

Dividing throughout by I_{dc}, we get:

$$\frac{I_{ac}}{I_{dc}} = \frac{1}{I_{dc}}\sqrt{I_{rms}^2 - I_{dc}^2}$$

As I_{ac}/I_{dc} is the ripple factor, as a result the ripple factor is:

$$\text{Ripple factor}, \gamma = \frac{1}{I_{dc}}\sqrt{I_{rms}^2 - I_{dc}^2} = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

Then, as a result, we can derive the ripple factors for half-wave and full-wave rectifiers.

b. For a half-wave rectifier circuit, the RMS and DC currents of the circuit are:

$$I_{rms} = \frac{I_m}{2} \qquad \text{and} \qquad I_{dc} = \frac{I_m}{\pi}$$

As a result, the ripple factor for half-wave rectifier is:

$$\text{Halwave ripple factor}, \gamma_{HW} = \sqrt{\left(\frac{I_m/2}{I_m/\pi}\right)^2 - 1} = 1.21$$

c. For a full-wave rectifier circuit, the RMS and DC currents of the circuit are:

$$I_{rms} = \frac{I_m}{\sqrt{2}} \qquad \text{and} \qquad I_{dc} = \frac{2I_m}{\pi}$$

As a result, the ripple factor of full-wave rectifier is:

$$\text{Fullwave ripple factor}, \gamma_{FW} = \sqrt{\left(\frac{I_m/\sqrt{2}}{2I_m/\pi}\right)^2 - 1} = 0.48$$

Thus

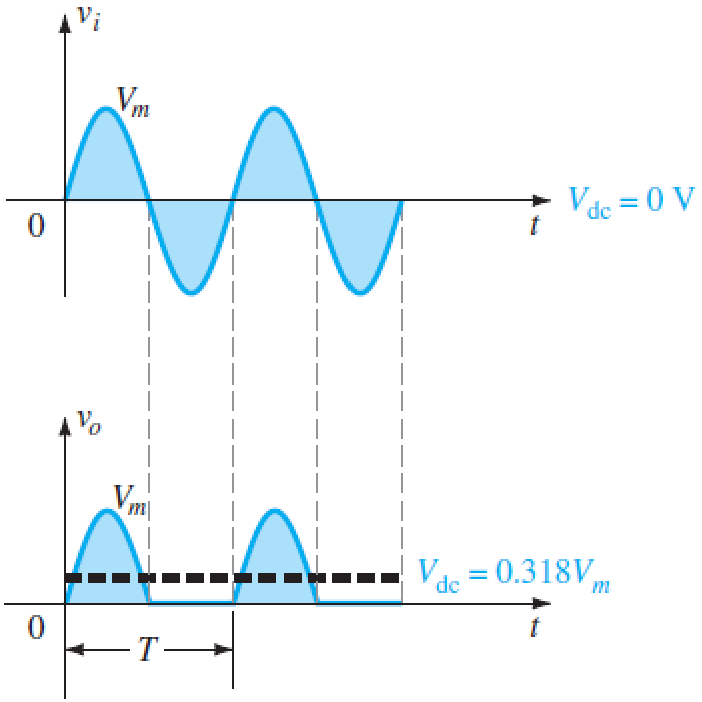
$$\gamma_{FW} = \frac{\text{Effective AC component}}{\text{DC component}} = 0.48$$

Clipper Networks

- Clipper circuits (also called voltage limiter circuits) are diode networks that can "clip" an incoming signal without distorting the remaining waveform.

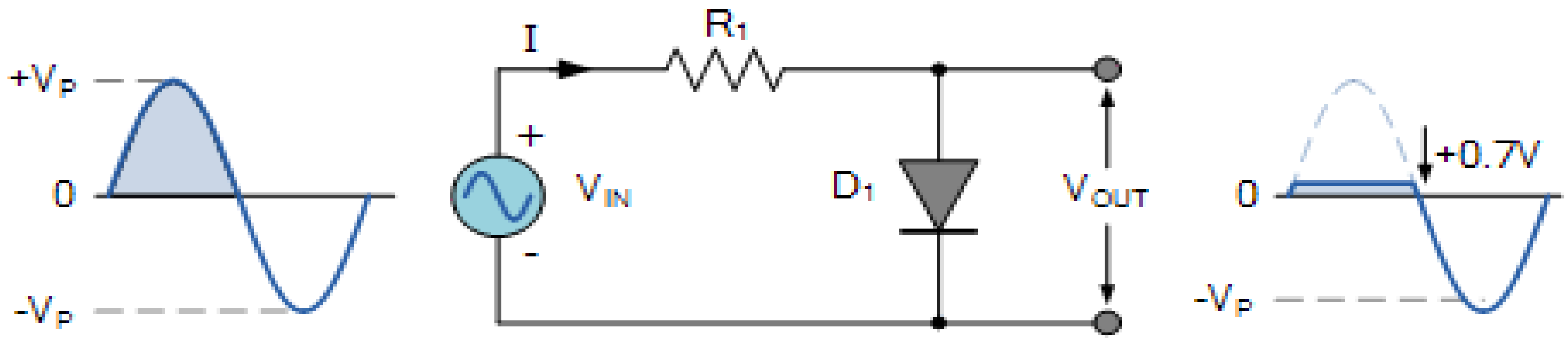
- They will eliminate portions of the signal above or below a certain specified level.

- The half-wave rectifier can then be called a clipper circuit as well, as all voltages below V_i = 0 V has cut-off (for positive cycle half-wave rectifier).



Example of a single diode clipper circuit

Positive diode clipper circuit (note where output is taken)

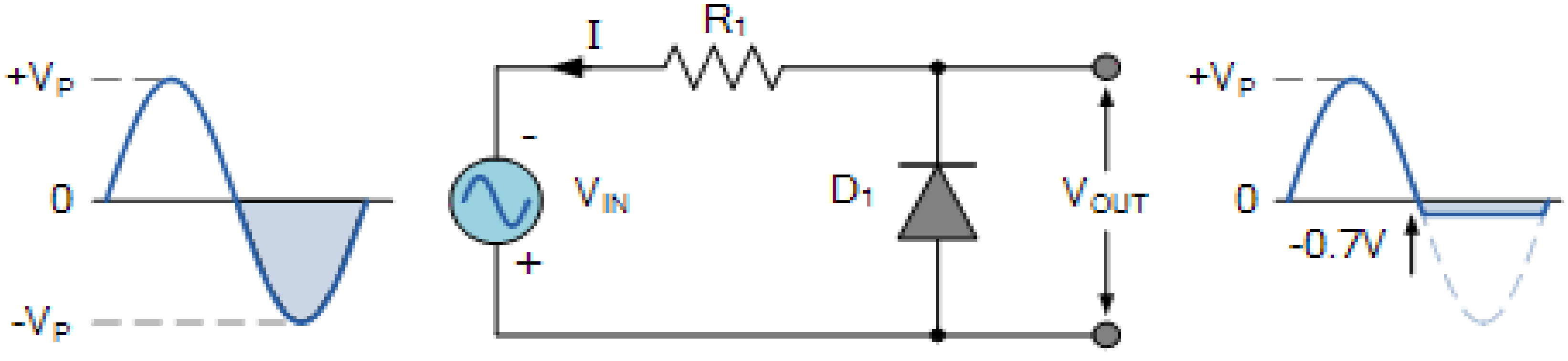


Treating the diode as an ideal diode plus voltage source:

- In forward bias, we get a constant voltage drop of ~ 0.7 V across the diode when V_i ≥ 0.7 V as the diode will then be switched ON.
- In reverse bias, or when V_i < 0.7 V, we will have V_i across the diode. All voltages where V_i ≥ 0.7 V is cut off from the output.

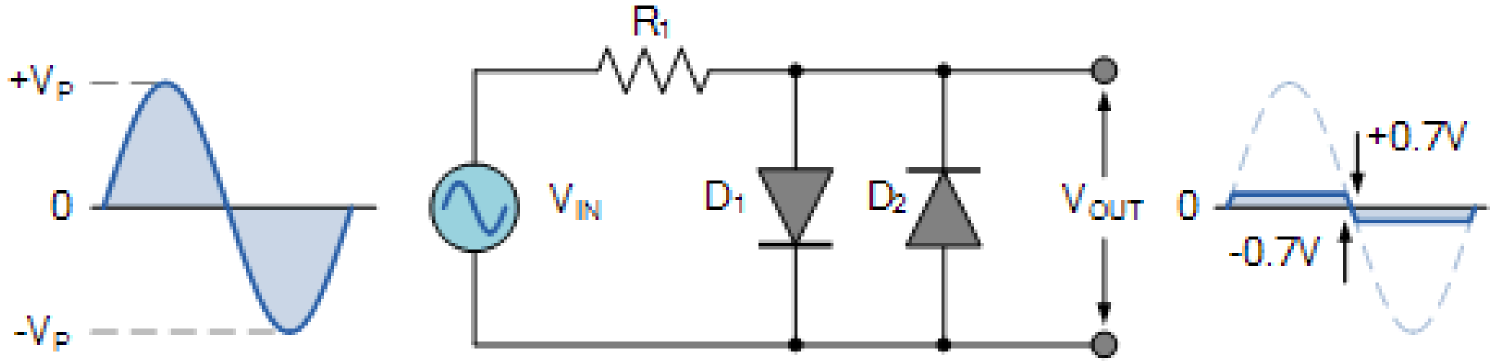
Negative diode clipper circuit

- Here the reverse is true from positive diode clipper.
- The diode is forward biased during the negative half cycle of the sinusoidal waveform and limits or clips it to -0.7 V while allowing the positive half cycle to pass unaltered when reverse biased.
- As the diode limits the negative half cycle of the input voltage, it is therefore called a negative clipper circuit.

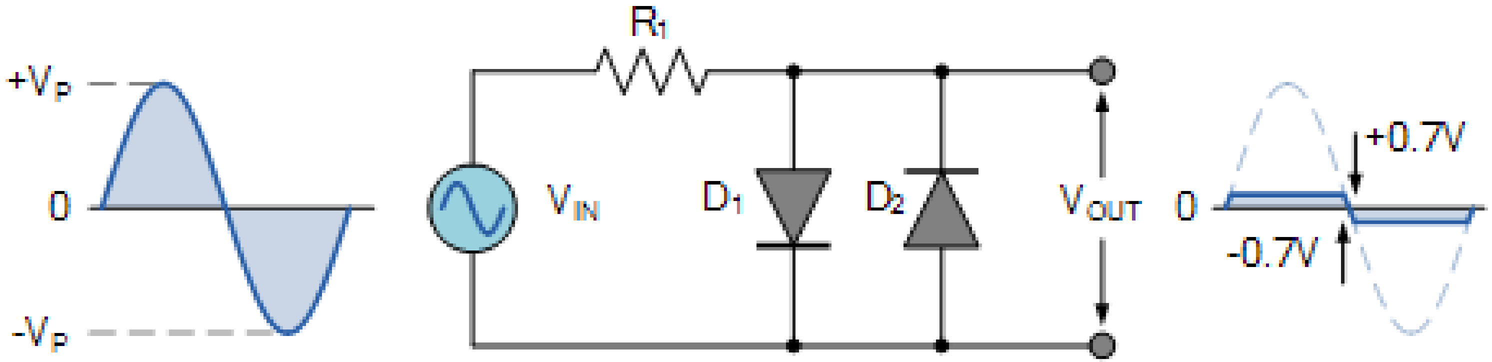


Clipping both cycles

- If we connected two diodes in inverse parallel as shown, then both the positive and negative half cycles would be clipped as diode D_1 clips the positive half cycle of the sinusoidal input waveform while diode D_2 clips the negative half cycle.
- Then diode clipping circuits can be used to clip the positive half cycle, the negative half cycle or both.

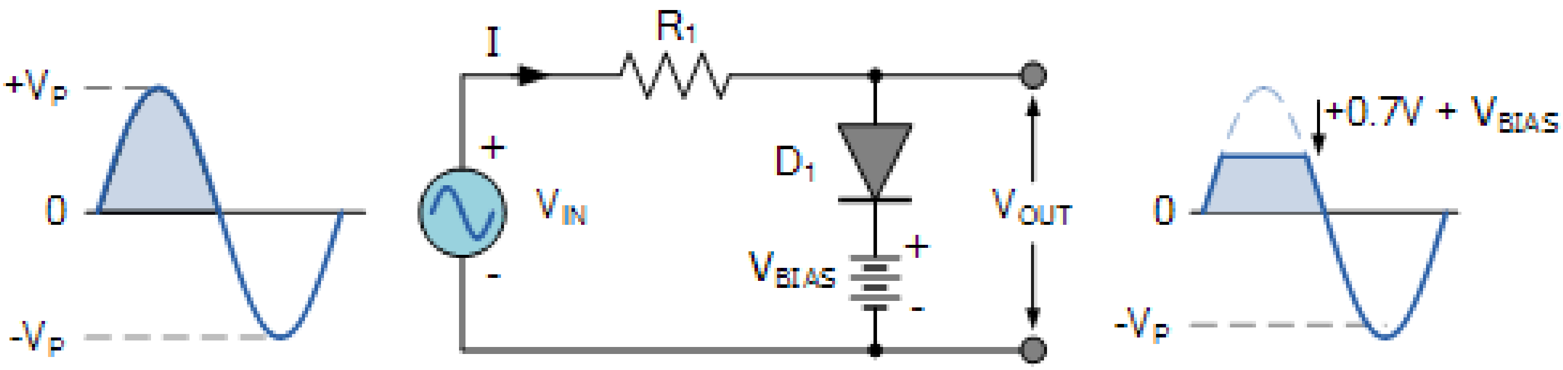


- For ideal diodes the output waveform above is zero.
- However, due to the forward bias voltage drop across the diodes the actual clipping point occurs at +0.7 V and -0.7 V respectively.
- But, we can increase this ± 0.7 V threshold to any value we want up to the maximum value, (V_{peak}) of the sinusoidal waveform, either by connecting together more diodes in series creating multiples of 0.7 V, or by adding a voltage bias to the diodes.

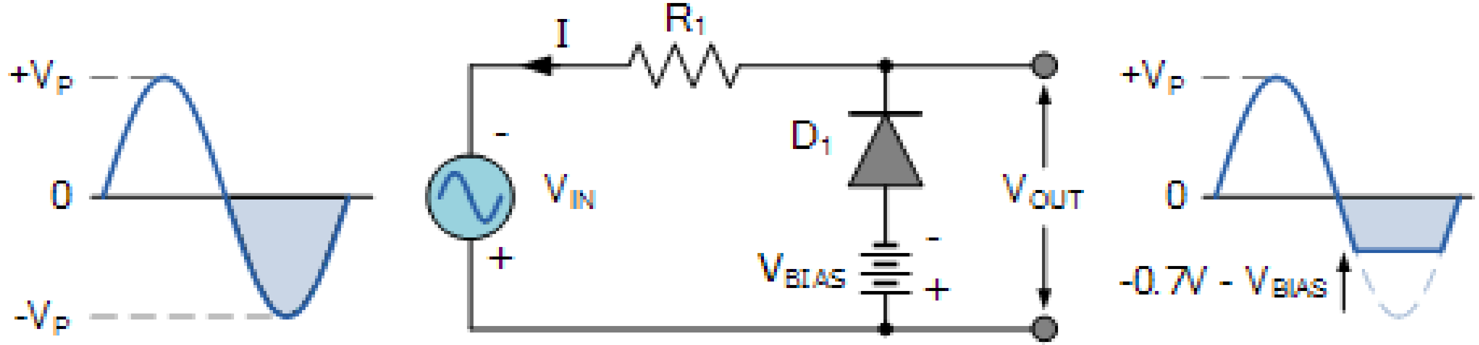


Biased clipping circuits

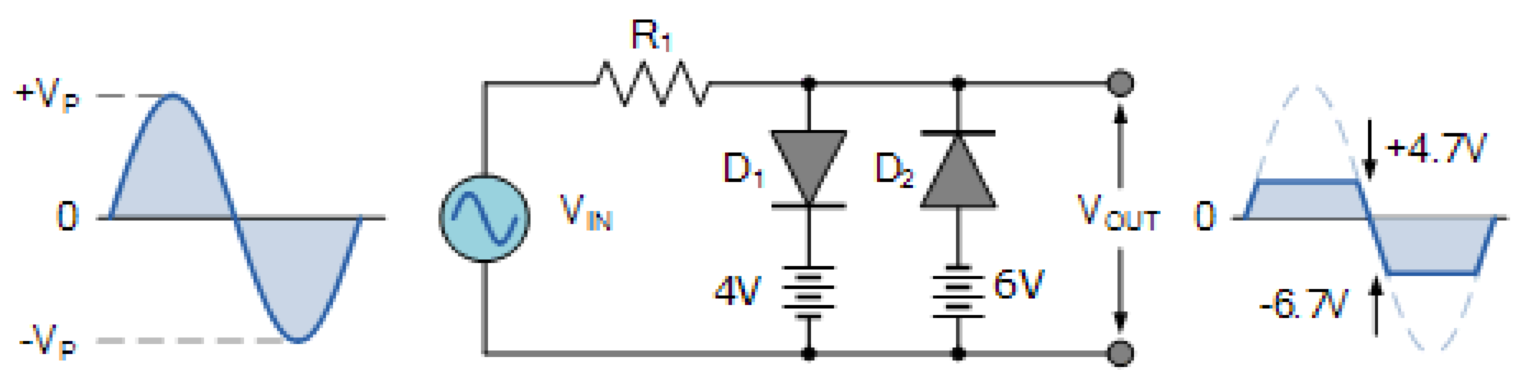
- To produce diode clipping circuits for voltage waveforms at different levels, a bias voltage, V_{bias} is added in series with the diode as shown.
- The voltage across the series combination must be greater than V_{bias} + 0.7 V before the diode becomes sufficiently forward biased to conduct.



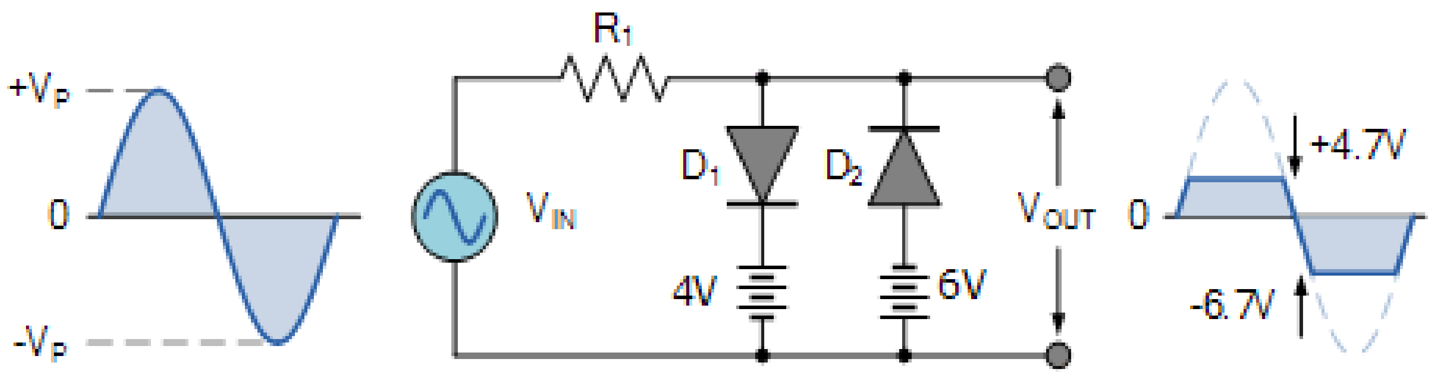
- For example, if the V_{bias} level is set at 4.0 V, then the sinusoidal voltage at the diode's anode terminal must be greater than 4.0 + 0.7 = 4.7 V for it to become forward biased.
- Any anode voltage levels above this bias point are clipped off.



- A variable diode clipping or diode limiting level can be achieved by varying the bias voltage of the diodes.
- If both the positive and the negative half cycles are to be clipped, then two biased clipping diodes are used.
- But, for both positive and negative diode clipping, the bias voltage need not be the same.
- The positive bias voltage could be at one level, for example 4 V, and the negative bias voltage at another, for example 6 V as shown.

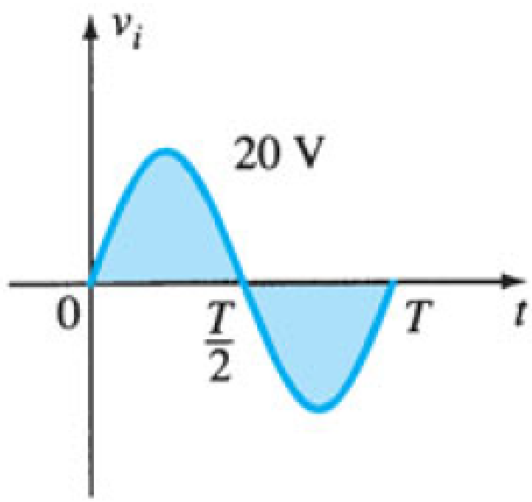


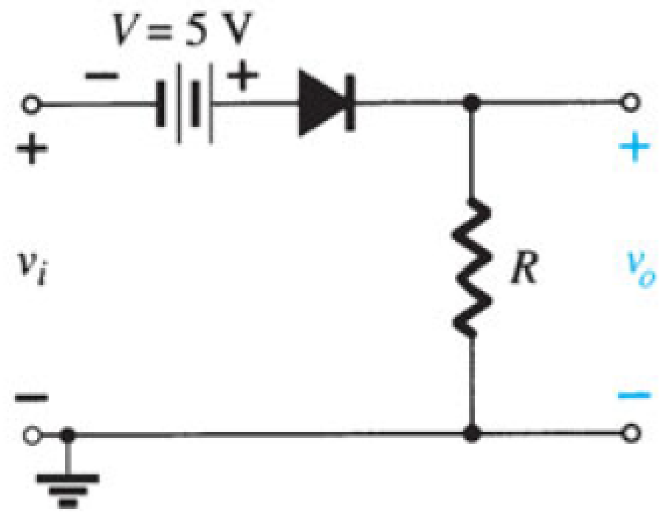
- When the voltage of the positive half cycle reaches +4.7 V, diode D_1 conducts and limits the waveform at +4.7 V.
- Diode D_2 does not conduct until the voltage reaches –6.7 V.
- Therefore, all positive voltages above +4.7 V and negative voltages below –6.7 V are automatically clipped.



Example for Tutorial 5 – Clipper Circuits

1. Determine the output waveform for the sinusoidal input of the circuit shown below. The output is taken directly across the resistor R. [8 marks]





Answer

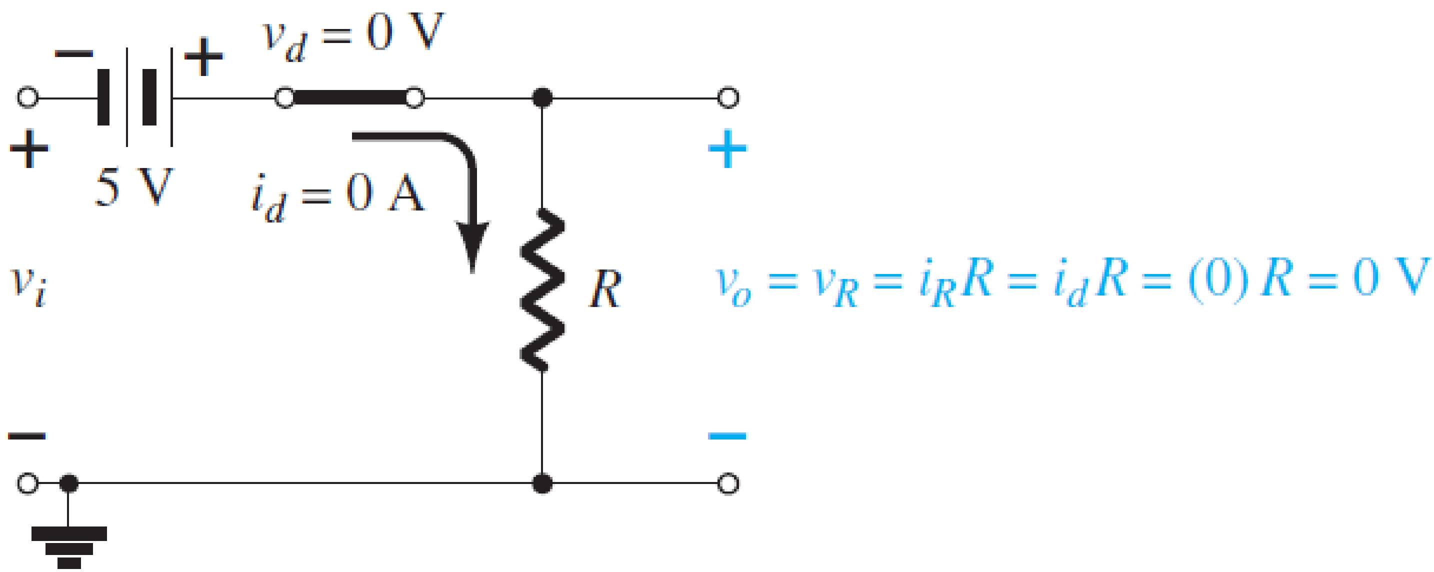
The positive region of v_i and the dc supply are both applying "pressure" to turn the diode on.

The result is that we can safely assume the diode is in the "on" state for the entire range of positive voltages for v_i.

Once the supply goes negative, it would have to exceed the dc supply voltage of 5 V before it could turn the diode off.

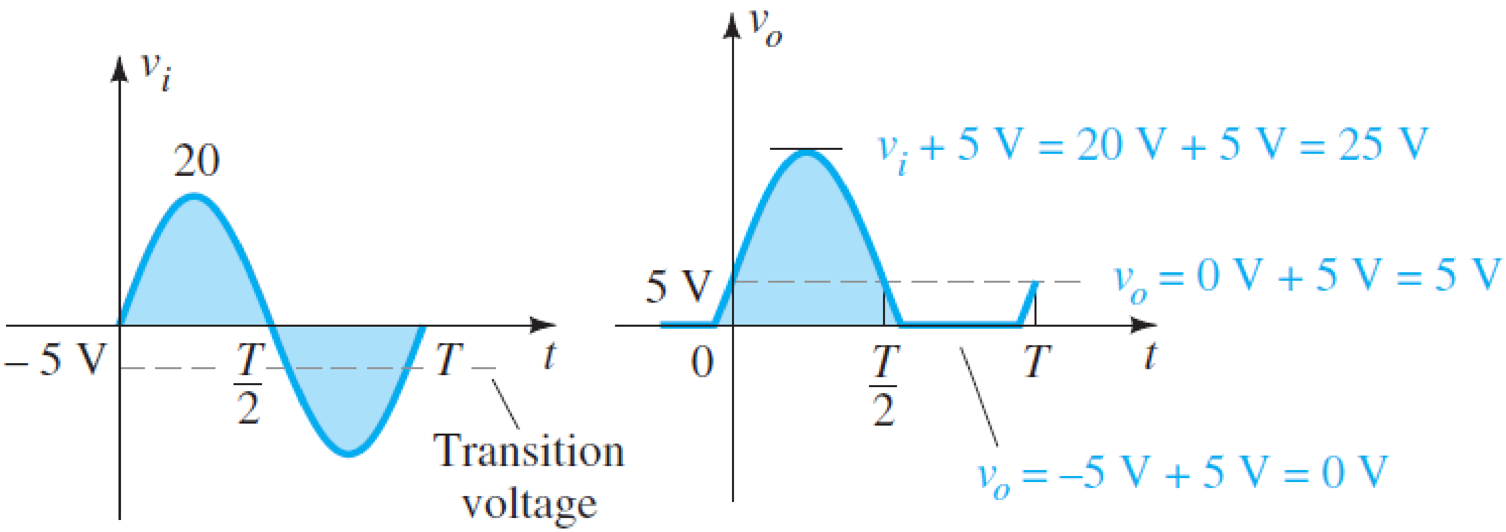
The transition model is substituted in the figure below, and we find that the transition from one state to the other will occur when:

$$v_i + 5 = 0 \qquad \text{or} \qquad v_i = -5 \text{ V}$$



In the figure below, a horizontal line is drawn through the applied voltage at the transition level.

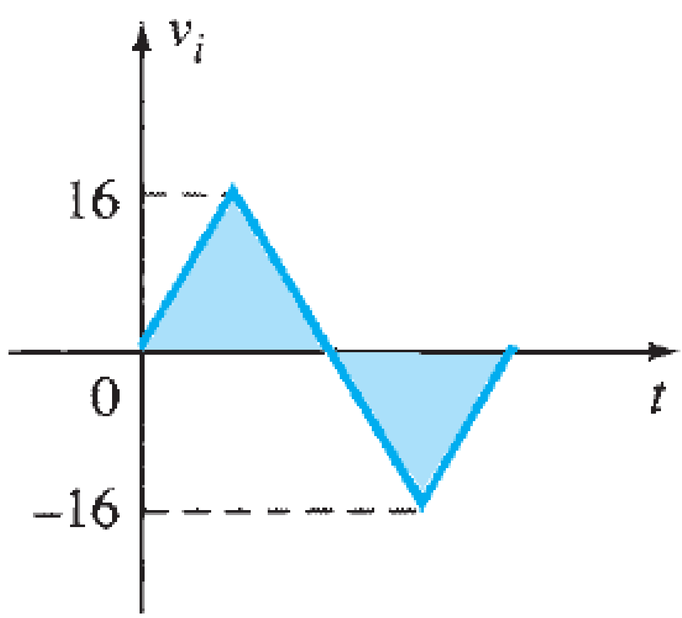
For voltages less than -5 V the diode is in the open-circuit state and the output is 0 V, as shown in the sketch of v_o.

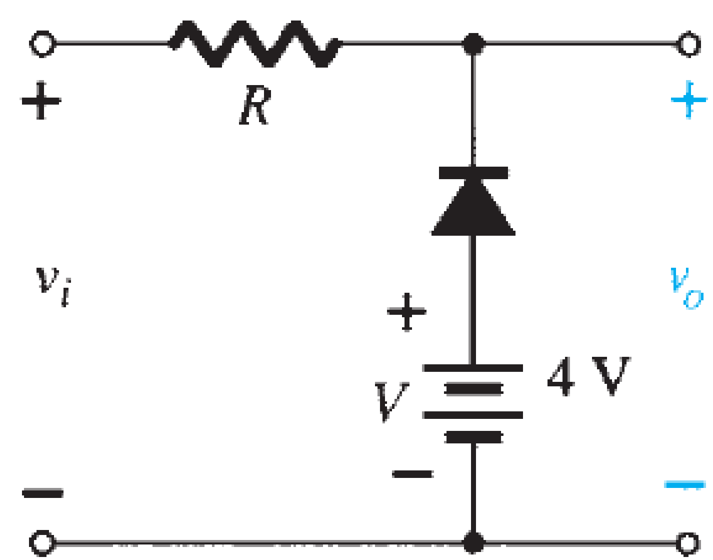


Using the figure above, we find that for conditions when the diode is on and the diode current is established the output voltage will be the following, as determined using Kirchhoff's voltage law:

$$v_o = v_i + 5$$

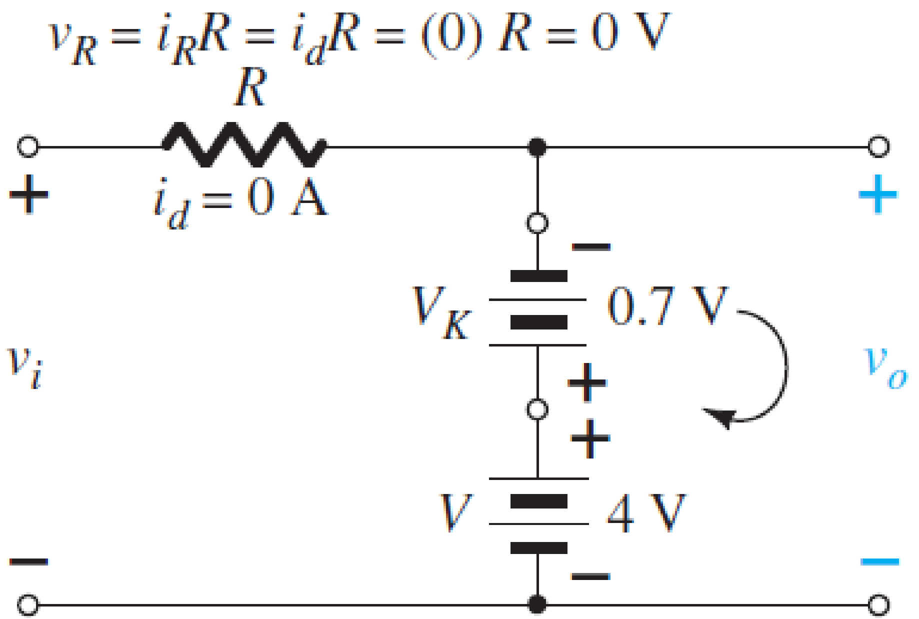
2. Determine v_o for the network of the circuit given below. In this example the output is defined across the series combination of the 4-V supply and the diode using a silicon diode with V_K = 0.7 V. [12 marks]





Answer

The transition voltage can first be determined by applying the condition i_d = 0 A at $v_d = V_D$ = 0.7 V and obtaining the network of the figure below.



Applying Kirchhoff's voltage law around the output loop in the clockwise direction, we find that:

$$v_i + V_K - V = 0$$

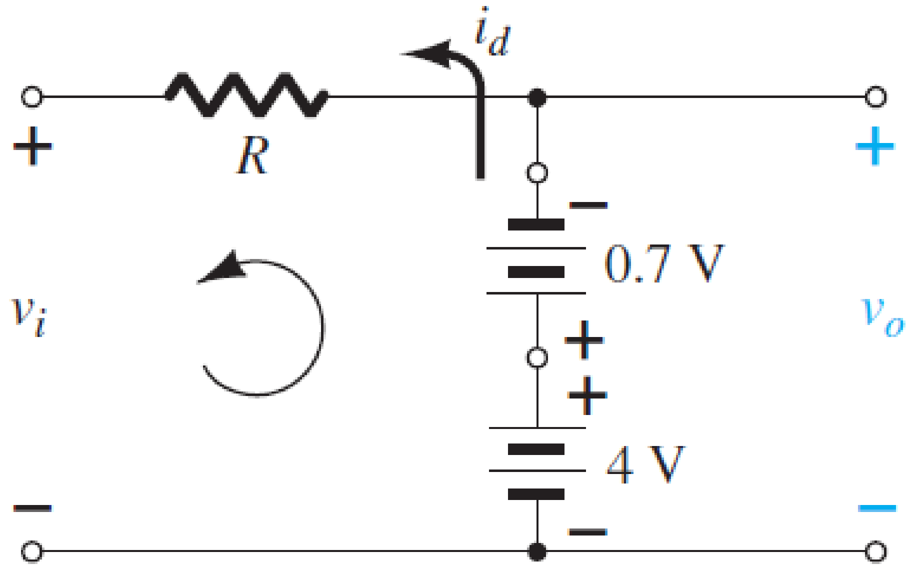
And

$$v_i = V - V_K = 4 - 0.7 = 3.3$$

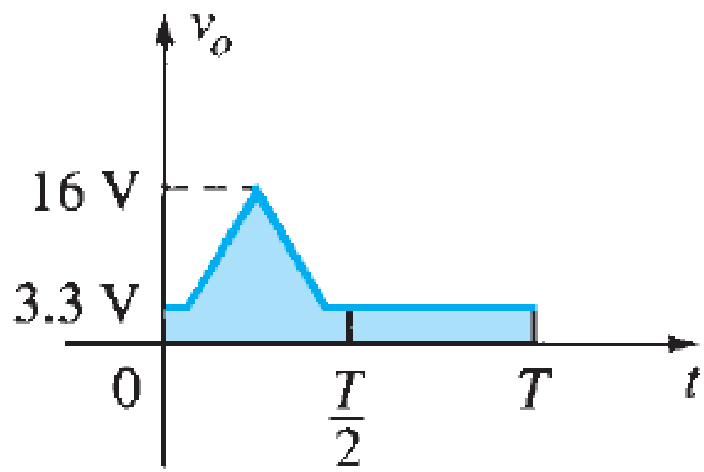
For input voltages greater than 3.3 V, the diode will be an open circuit and $v_o = v_i$.

For input voltages less than 3.3 V, the diode will be in the "on" state and the network of the circuit results given below, where:

$$v_o = 4 - 0.7 = 3.3$$



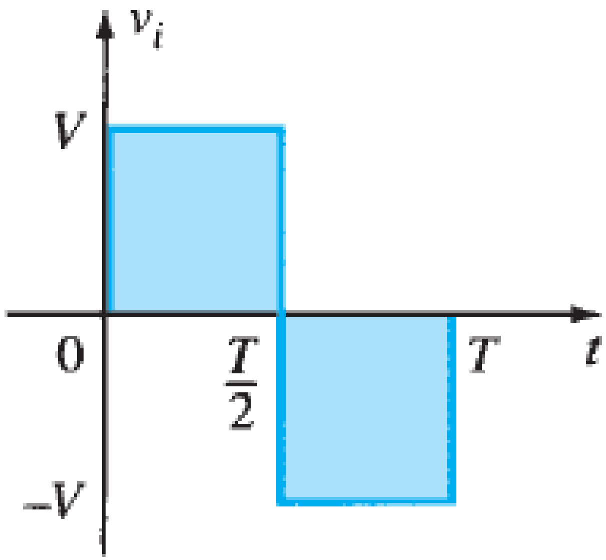
The resulting output waveform appears in the figure below. Note that the only effect of V_K was to drop the transition level to 3.3 from 4 V.

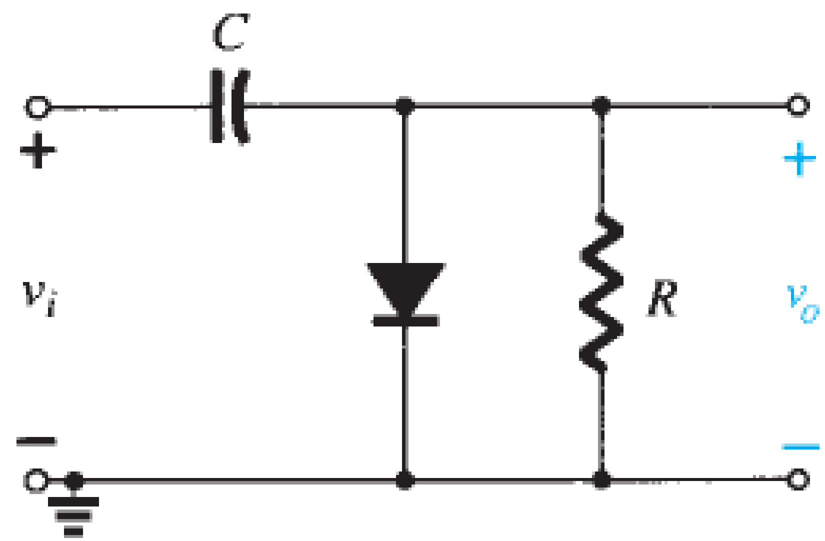


Clamping Circuits

- These circuits will clamp an AC signal to a different voltage level – also called *AC shifter circuits*.
- These circuits should contain the following elements:
  - Diode.
  - Resistor.
  - Capacitor.
  - Independent DC supply to introduce a shift.
- The time constant of RC must be chosen so that it is long enough that the capacitor does not discharge significantly during the time that the diode is OFF.

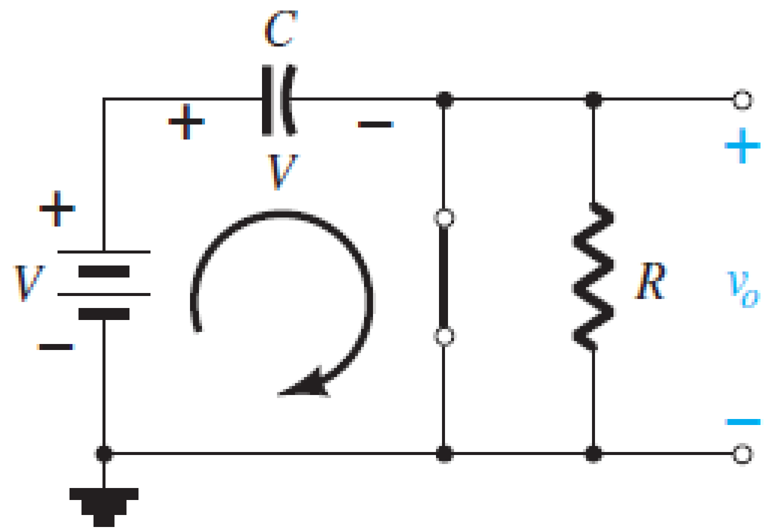
This circuit given below is clamping the signal to the zero level (ideal diode).





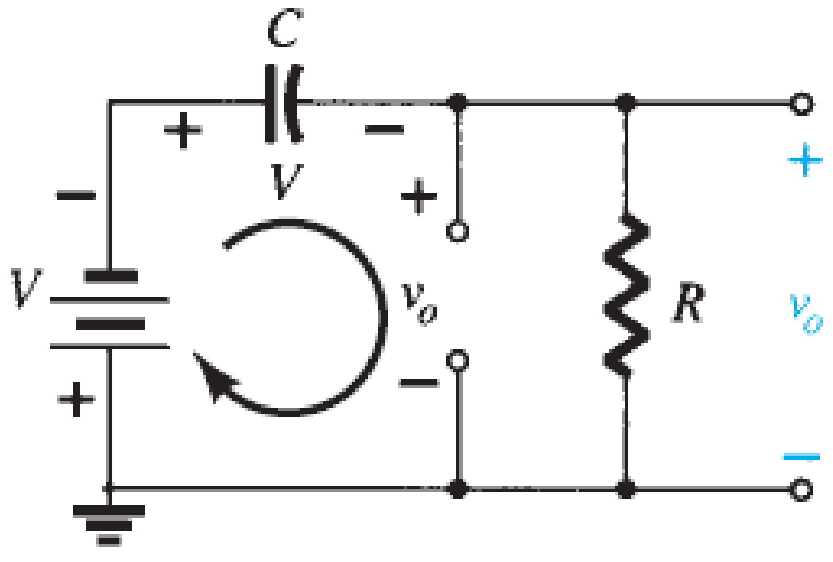
For the period $0 < t < T/2$:

- Diode in forward bias and ON.
- This will short out diode so that capacitor charges quickly through diode.
- C charges up to voltage V.
- Output voltage during this time is output over shorted diode, hence $V_o = 0$ V.



For the period $T/2 < t < T$:

- Diode is in reverse bias and OFF.
- The diode now appears as an open circuit, but diode will discharge through the capacitor.
- With a long time constant RC the charge (and thus voltage) will remain on capacitor until the end of the cycle.



Write a KVL around the loop:

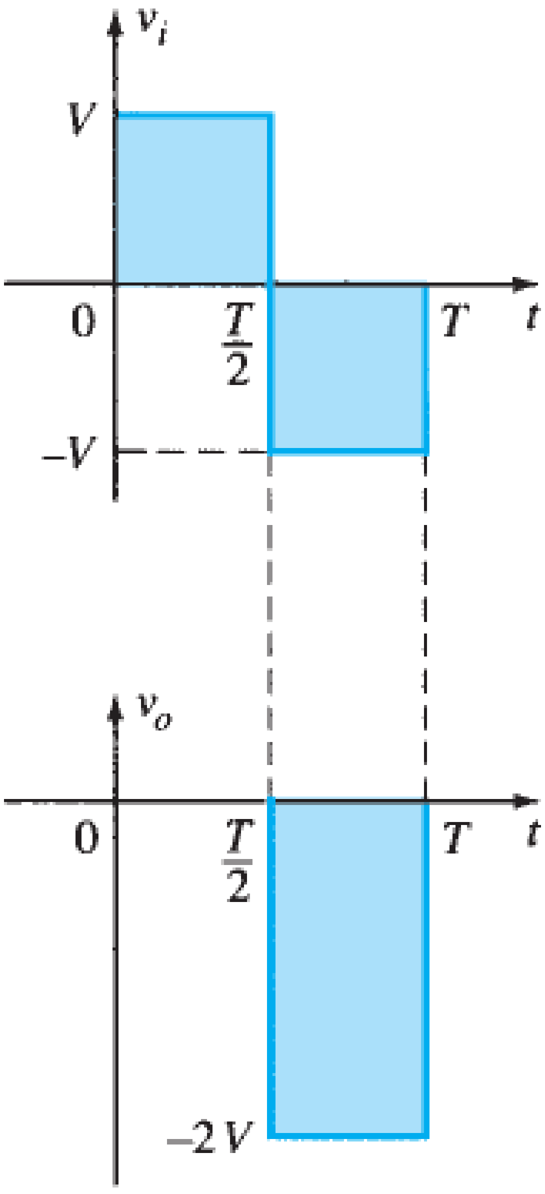
$$-V_s - V_c - V_o = 0$$

so that $V_s = V_c$

$$V_o = -2V_c = -2 \text{ V}$$

During negative input cycle to output will then be -2 V.

- Total voltage swing of input cycle appears over the negative output cycle.
- Zero level has shifted down by -1 V.



For clamping network as a general rule:

The total swing of the output signal is equal to the total swing of the input signal

Steps for analysing clamping networks:

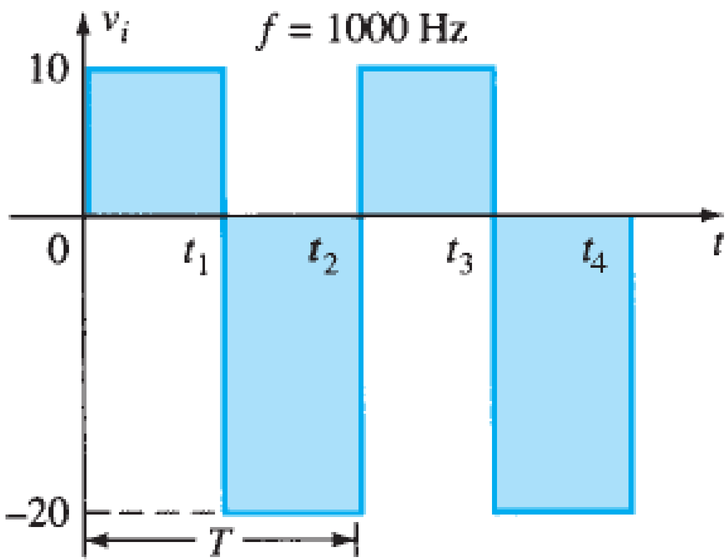
1. Start by considering that part of the input signal that will forward bias the diode.
2. During the diode ON time, assume the capacitor will charge up instantaneously to the voltage level as determined by the network.
3. Assume that during the diode OFF cycle the capacitor will maintain its charge i.e. hold its voltage level.
4. Keep polarity of V_o in mind at all times to ensure proper voltage level.
5. Total swing of the output should equal total swing of the input.

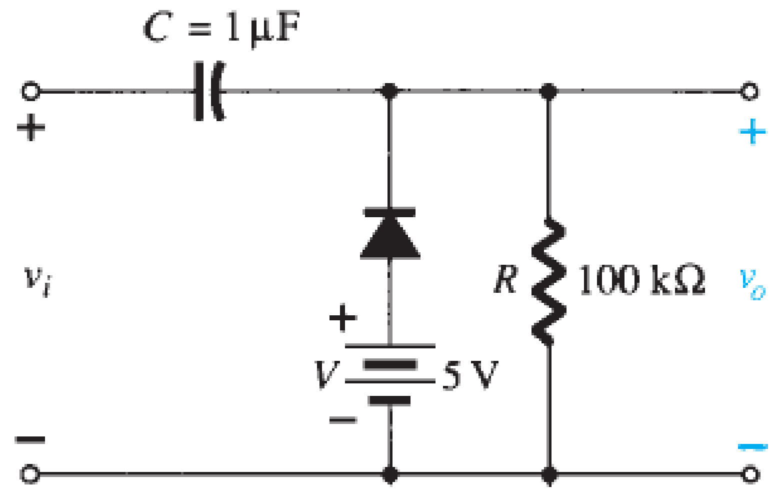
Biased Diode Clamper

As before, having voltage source connected with the diode, this time in a clamper circuit, enables the circuit that can clamp (e.g. limit) the input signal to a specific operational level the with additional voltage offset inserted.

Example for Tutorial 6 – Clamper Circuit with Bias Voltage

Determine V_o for the following network and input signal:

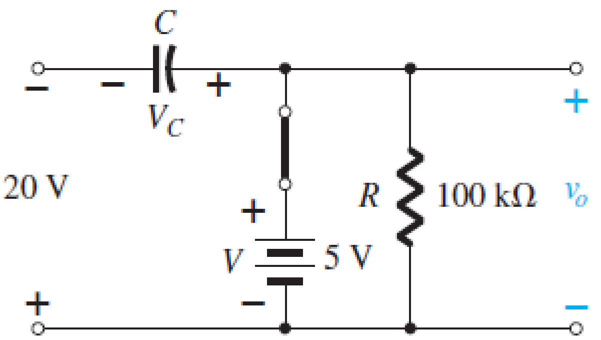




Answer

- Start analysis in period t_1 to t_2 in order to start with ON diode. Applying the KVL:

$$-20 + V_c - 5 = 0$$

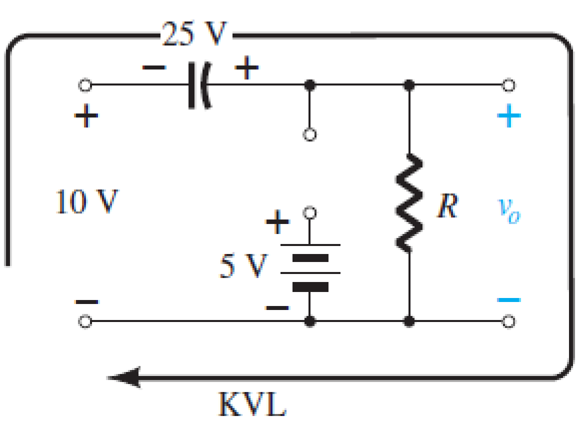


- Capacitor V_c charges to 25 V.

- Start analysis in period t_2 to t_3 in order to start with OFF diode. Applying the KVL:

$$10 + 25 - V_o = 0$$

$$V_o = 35 \text{ V}$$



- Time constant of circuit

$$\tau = RC = (100 \times 10^3)(0.1 \times 10^{-6}) = 0.01\ s$$