Diode Circuits: Part 2

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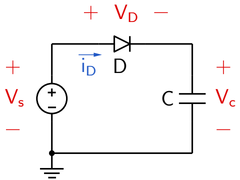
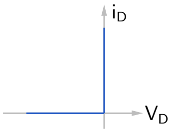
Peak detector (with $V_{on} = 0\,\mathrm{V}$)



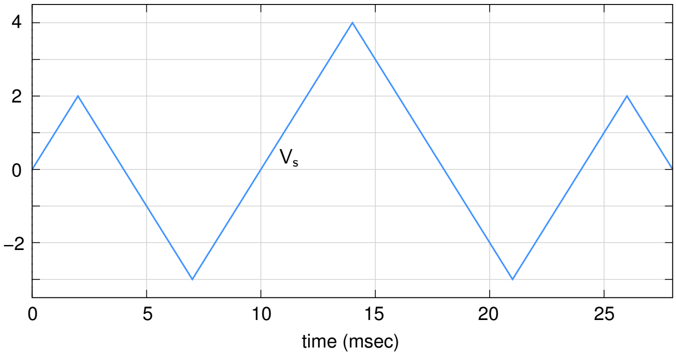


$V_c(0) = 0\,\mathrm{V}$

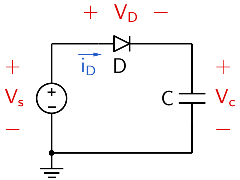
$V_{on} = 0\,\mathrm{V}$

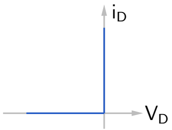
$R_{on} \to 0\,\Omega$

$R_{off} \to \infty\,\Omega$

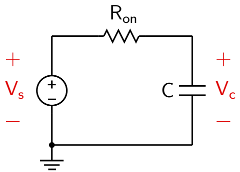


Peak detector (with $V_{on} = 0\,\mathrm{V}$)

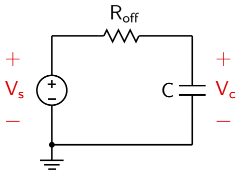




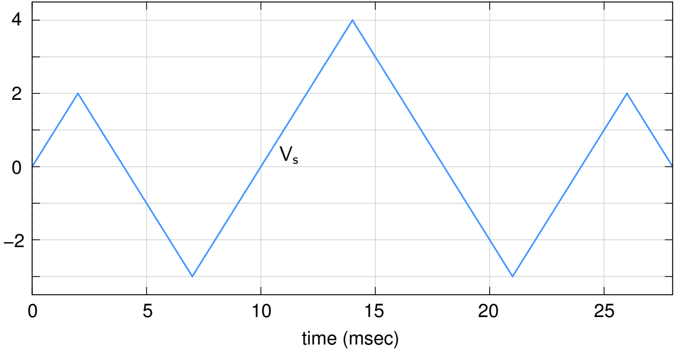
$V_c(0) = 0\,\mathrm{V}$
$V_{on} = 0\,\mathrm{V}$
$R_{on} \to 0\,\Omega$
$R_{off} \to \infty\,\Omega$



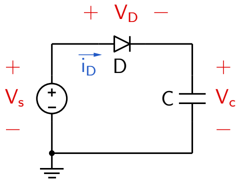
$V_s > V_c$
$\tau = R_{on} C$

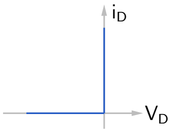


$V_s < V_c$
$\tau = R_{off} C$



Peak detector (with $V_{on} = 0\,\mathrm{V}$)



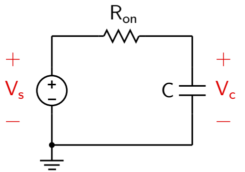


$V_c(0) = 0\,\mathrm{V}$

$V_{on} = 0\,\mathrm{V}$

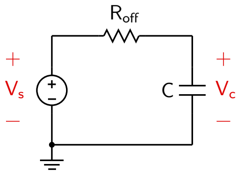
$R_{on} \rightarrow 0\,\Omega$

$R_{off} \rightarrow \infty\,\Omega$



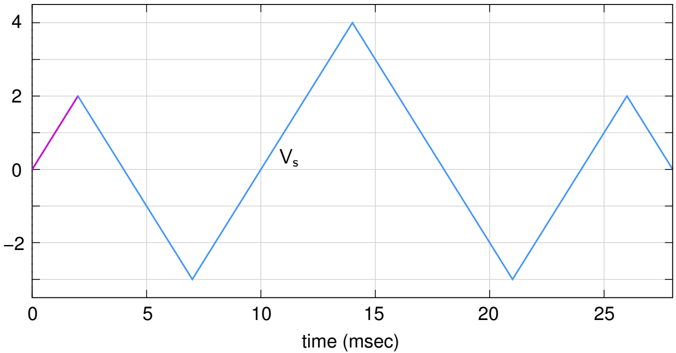
$V_s > V_c$

$\tau = R_{on} C$

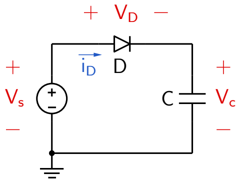


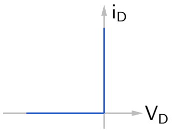
$V_s < V_c$

$\tau = R_{off} C$



Peak detector (with $V_{on} = 0\,\mathrm{V}$)



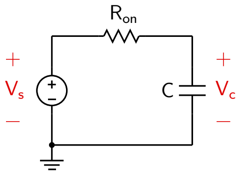


$V_c(0) = 0\,\mathrm{V}$

$V_{on} = 0\,\mathrm{V}$

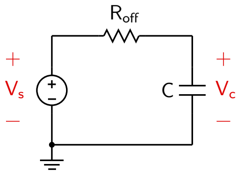
$R_{on} \to 0\,\Omega$

$R_{off} \to \infty\,\Omega$



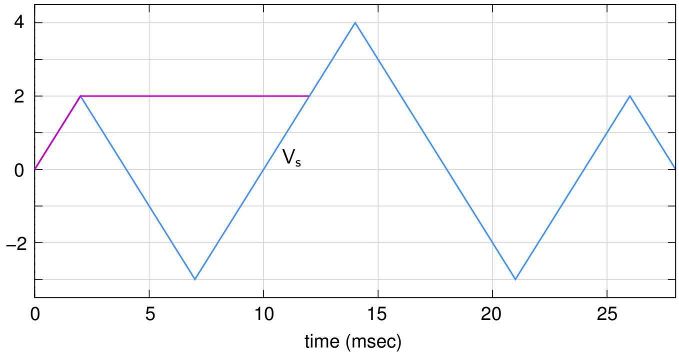
$V_s > V_c$

$\tau = R_{on} C$

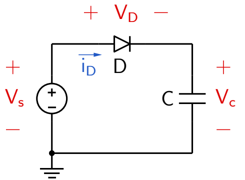


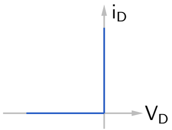
$V_s < V_c$

$\tau = R_{off} C$



Peak detector (with $V_{on} = 0\,\mathrm{V}$)





$V_c(0) = 0\,\mathrm{V}$

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$R_{on} \rightarrow 0\,\Omega$

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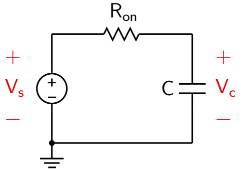

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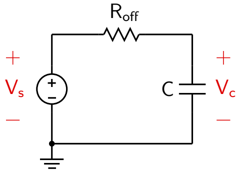
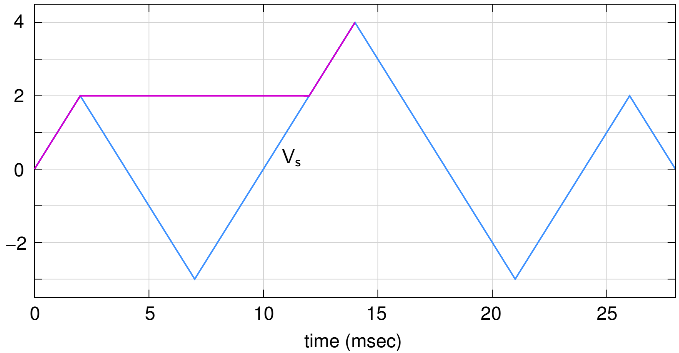
$\tau = R_{on}C$

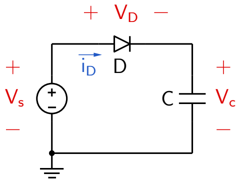


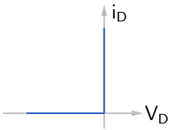
$V_s < V_c$

$\tau = R_{off}C$



Peak detector (with $V_{on} = 0\,\text{V}$)





$V_c(0) = 0\,\text{V}$

$V_{on} = 0\,\text{V}$

$R_{on} \rightarrow 0\,\Omega$

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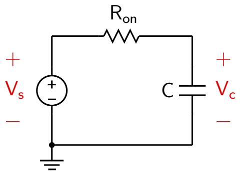

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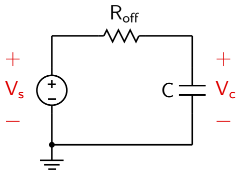
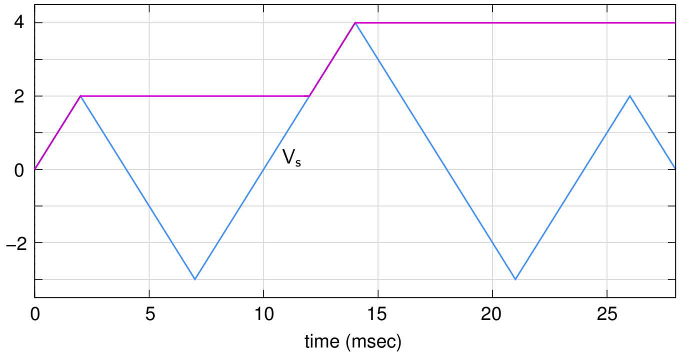
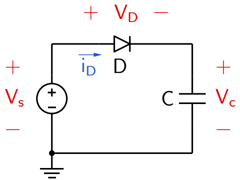


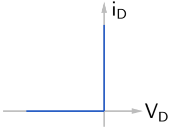
$V_s < V_c$

$\tau = R_{off} C$



Peak detector (with $V_{on} = 0\,V$)



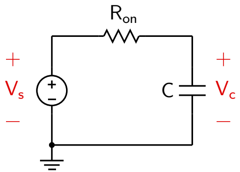


$V_c(0) = 0\,V$

$V_{on} = 0\,V$

$R_{on} \rightarrow 0\,\Omega$

$R_{off} \rightarrow \infty\,\Omega$



$V_s > V_c$

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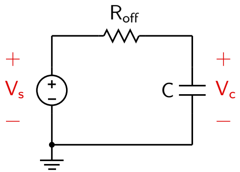
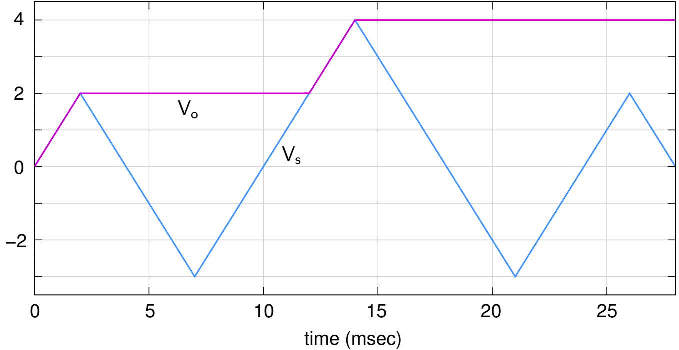


$V_s < V_c$

$\tau = R_{off} C$



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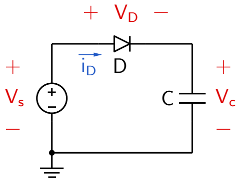
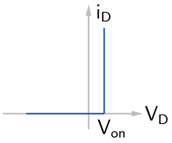
Peak detector (with $V_{on} = 0.7\,V$)



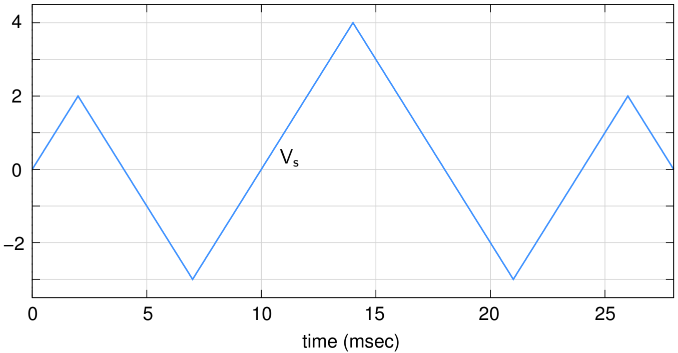


$V_c(0) = 0\,V$

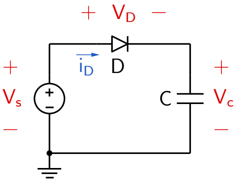
$V_{on} = 0.7\,V$

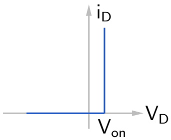
$R_{on} \to 0\,\Omega$

$R_{off} \to \infty\,\Omega$



Peak detector (with $V_{on} = 0.7\,\mathrm{V}$)



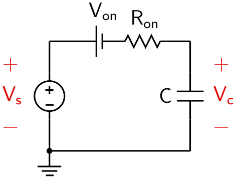


$V_c(0) = 0\,\mathrm{V}$

$V_{on} = 0.7\,\mathrm{V}$

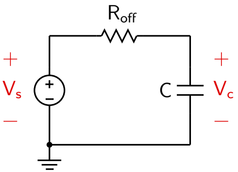
$R_{on} \to 0\,\Omega$

$R_{off} \to \infty\,\Omega$



$V_s > V_c + V_{on}$

$\tau = R_{on} C$



$V_s < V_c + V_{on}$

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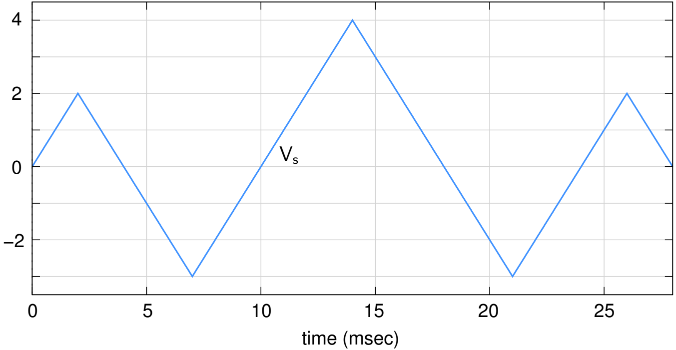
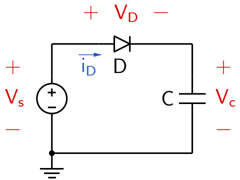
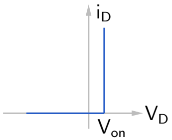


Peak detector (with $V_{on} = 0.7\,V$)



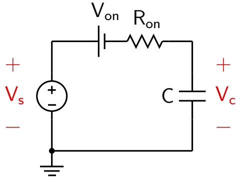


$V_c(0) = 0\,V$

$V_{on} = 0.7\,V$

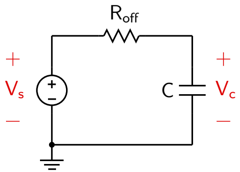
$R_{on} \rightarrow 0\,\Omega$

$R_{off} \rightarrow \infty\,\Omega$



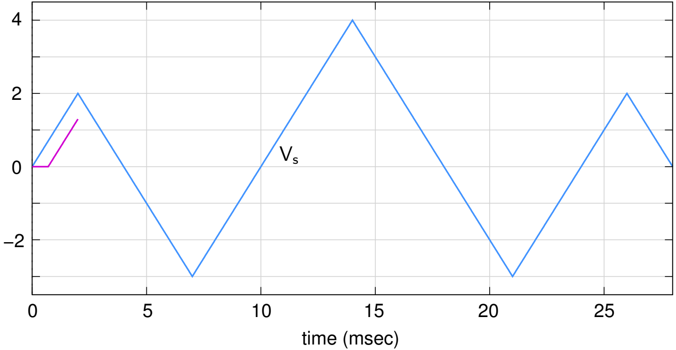
$V_s > V_c + V_{on}$

$\tau = R_{on} C$

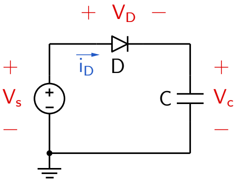


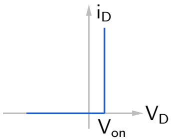
$V_s < V_c + V_{on}$

$\tau = R_{off} C$



Peak detector (with $V_{on} = 0.7\,\mathrm{V}$)



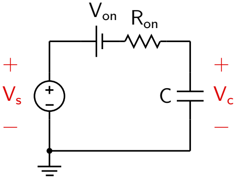


$V_c(0) = 0\,\mathrm{V}$

$V_{on} = 0.7\,\mathrm{V}$

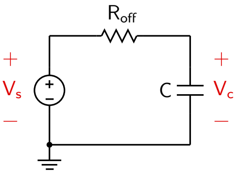
$R_{on} \to 0\,\Omega$

$R_{off} \to \infty\,\Omega$



$V_s > V_c + V_{on}$

$\tau = R_{on} C$



$V_s < V_c + V_{on}$

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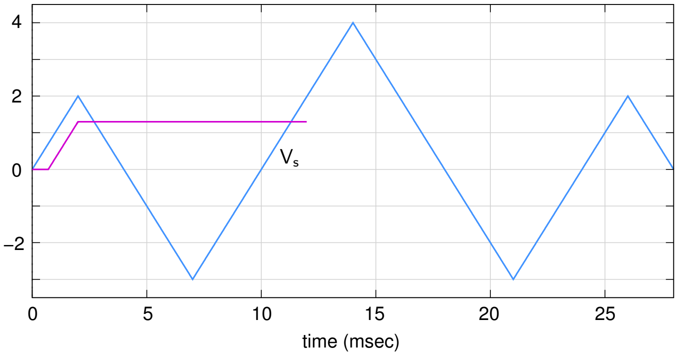
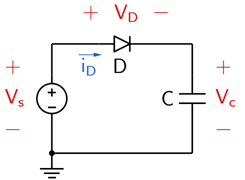
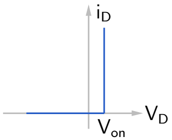


Peak detector (with $V_{on} = 0.7\,\text{V}$)





$V_c(0) = 0\,\text{V}$

$V_{on} = 0.7\,\text{V}$

$R_{on} \to 0\,\Omega$

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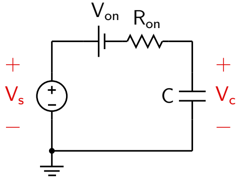

$V_s > V_c + V_{on}$

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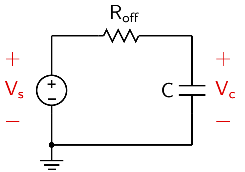

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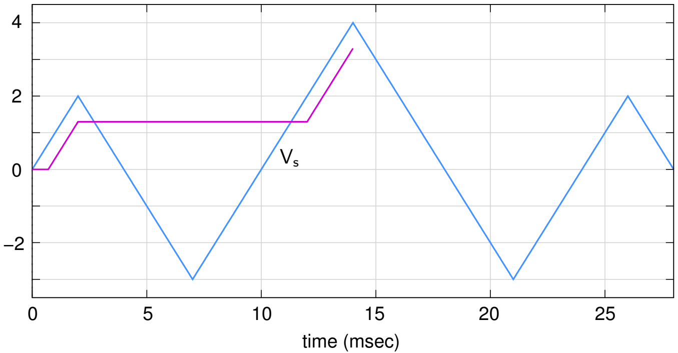
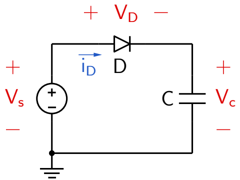
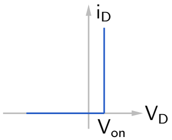


Peak detector (with $V_{on} = 0.7\,\mathrm{V}$)





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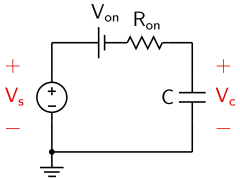

$V_s > V_c + V_{on}$

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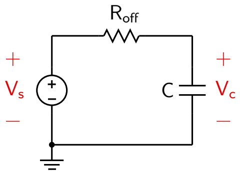

$V_s < V_c + V_{on}$

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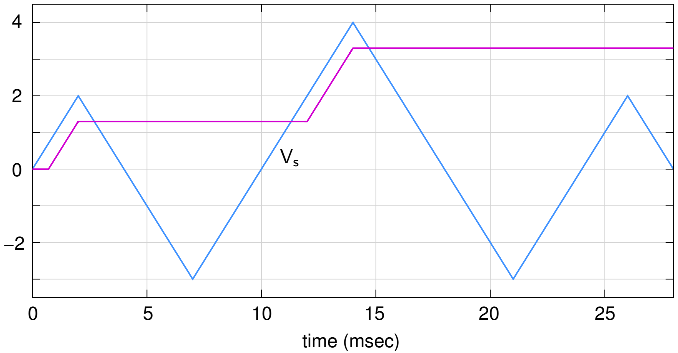
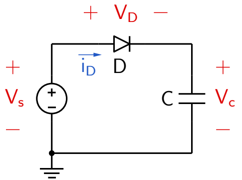
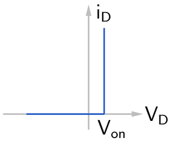


Peak detector (with $V_{on} = 0.7\,V$)



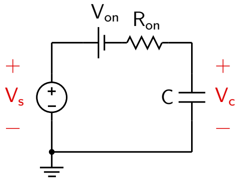


$V_c(0) = 0\,V$

$V_{on} = 0.7\,V$

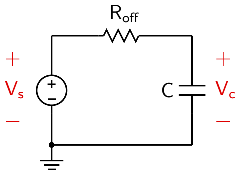
$R_{on} \rightarrow 0\,\Omega$

$R_{off} \rightarrow \infty\,\Omega$



$V_s > V_c + V_{on}$

$\tau = R_{on} C$



$V_s < V_c + V_{on}$

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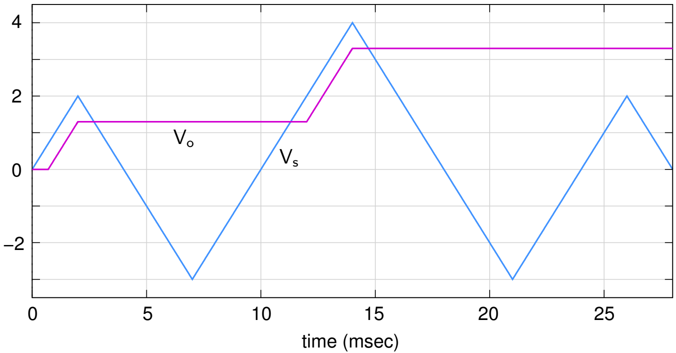
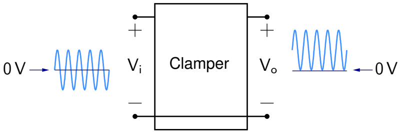


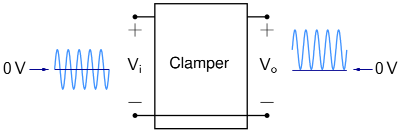
SEQUEL file: `ee101_peak_detector_1.sqproj`

Clamper circuits

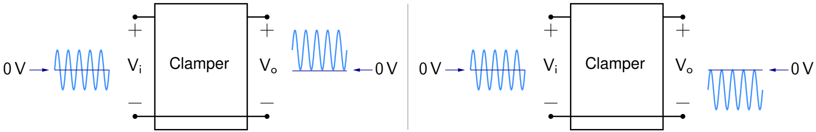


* A clamper circuit provides a "level shift." (The shape of the input signal is not altered.)

Clamper circuits



* A clamper circuit provides a "level shift." (The shape of the input signal is not altered.)
* The shift could be positive or negative.



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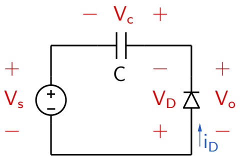
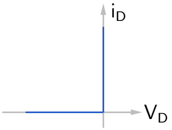
Clamper circuits





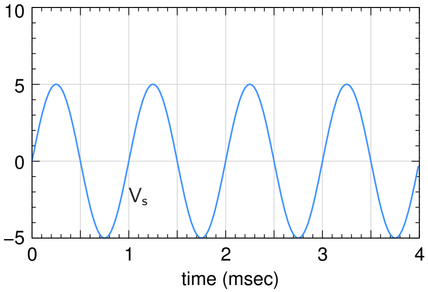
$V_s(t) = V_m \sin \omega t$

$V_c(0) = 0\,V$

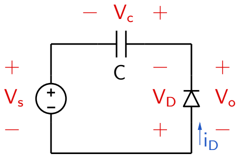
$V_{on} = 0\,V$

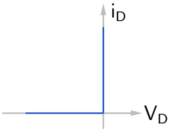
$R_{on} \rightarrow 0\,\Omega$

$R_{off} \rightarrow \infty\,\Omega$



Clamper circuits





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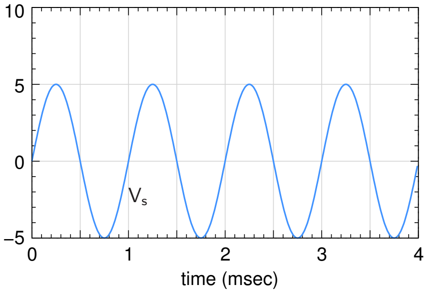
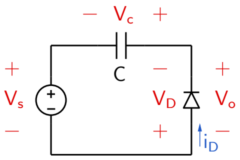
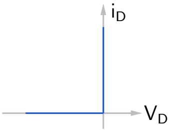


* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c + V_s = 0 \rightarrow V_c = -V_s$.

Clamper circuits





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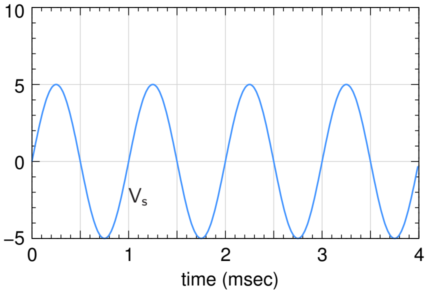

* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c + V_s = 0 \rightarrow V_c = -V_s$.
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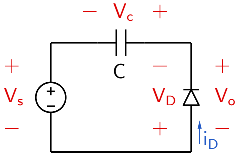
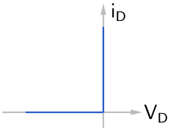
Clamper circuits





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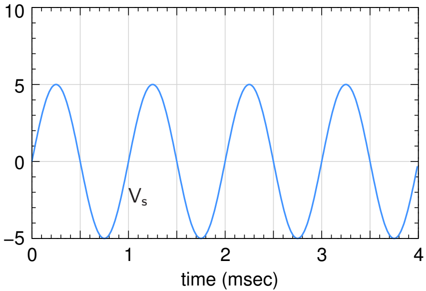

* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c + V_s = 0 \rightarrow V_c = -V_s$.
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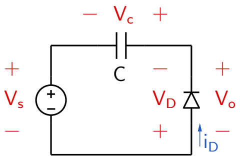
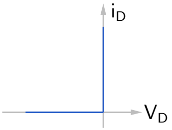
Clamper circuits





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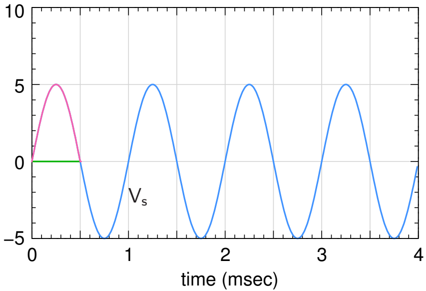

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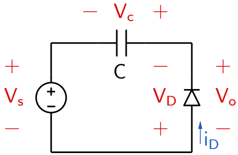

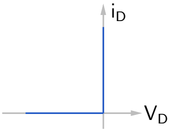

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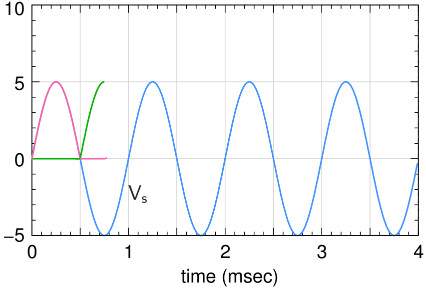

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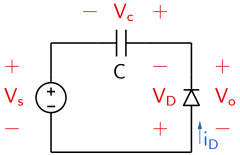

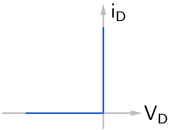

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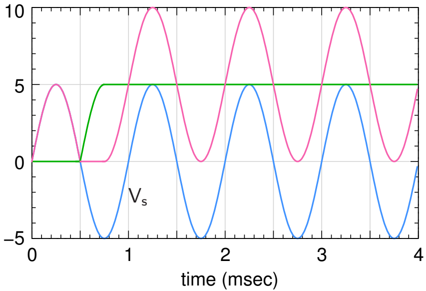

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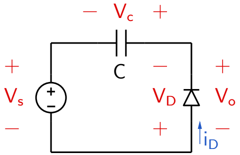
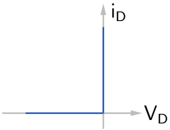
Clamper circuits





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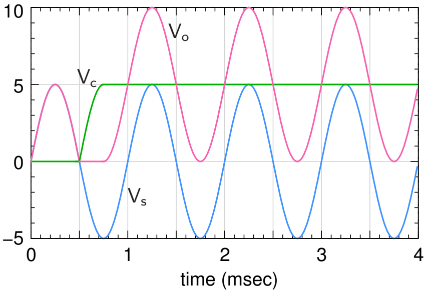

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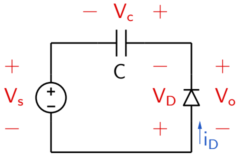
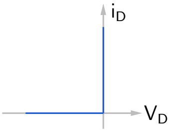
Clamper circuits





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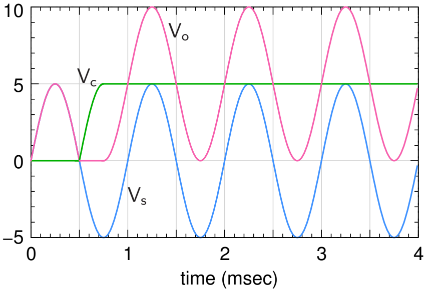

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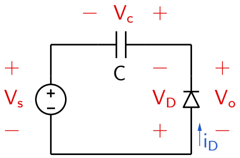
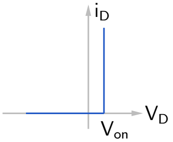
* Note that we are generally interested only in the steady-state behaviour and not in the transient at the beginning.





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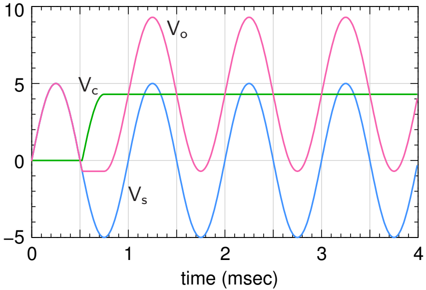

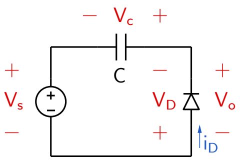

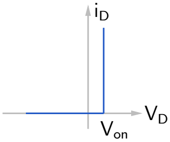

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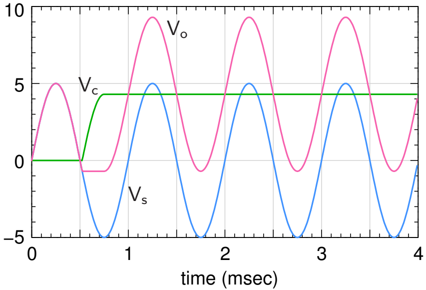
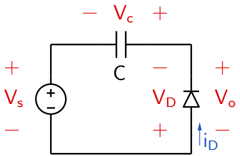
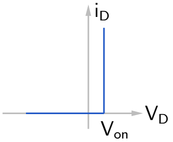


* When D conducts, the capacitor charges instantaneously since R_{on} is small (as in the last circuit). In this phase, $V_c + V_s + V_{on} = 0 \rightarrow V_c = -V_s - V_{on}$.

Clamper circuits





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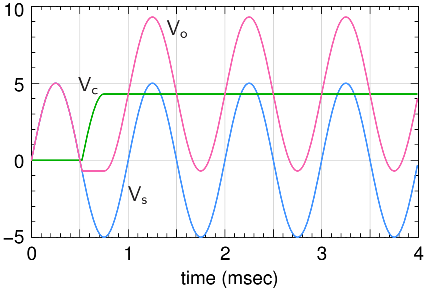

* When D conducts, the capacitor charges instantaneously since R_{on} is small (as in the last circuit).
  In this phase,
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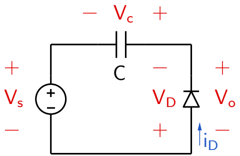
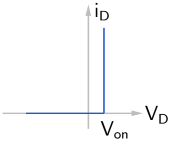
Clamper circuits





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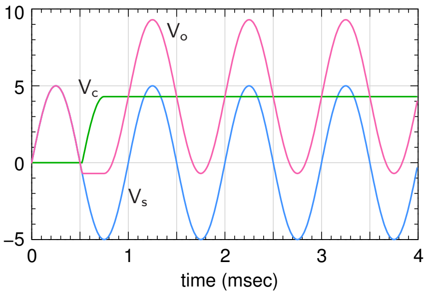

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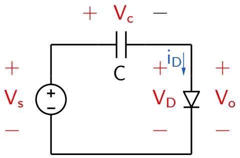
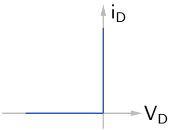
* After V_c reaches its maximum value $(V_m - V_{on})$, it cannot change any more. We then have
  $V_o(t) = V_s(t) + V_c(t) = V_s(t) + V_m - V_{on}$. In this case, V_o gets clamped at $-0.7\,\text{V}$.

Clamper circuits





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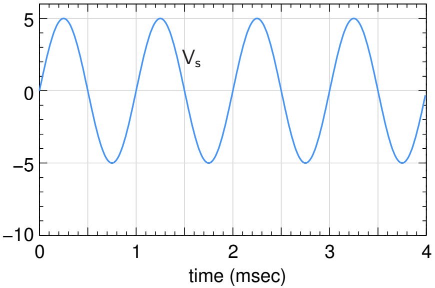
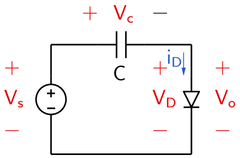
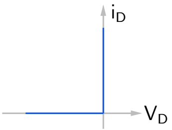


Clamper circuits





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$R_{on} \rightarrow 0\,\Omega$

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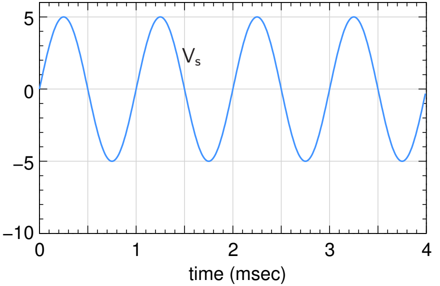
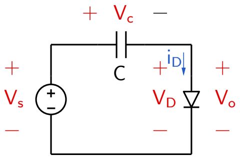
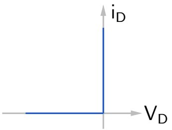


* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c - V_s = 0 \rightarrow V_c = V_s$.

Clamper circuits





$V_s(t) = V_m \sin \omega t$
$V_c(0) = 0\,V$
$V_{on} = 0\,V$
$R_{on} \rightarrow 0\,\Omega$
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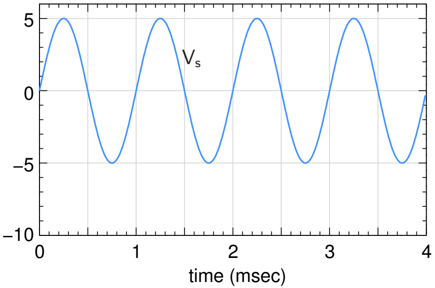
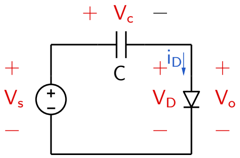
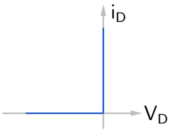


* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c - V_s = 0 \rightarrow V_c = V_s$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.

Clamper circuits





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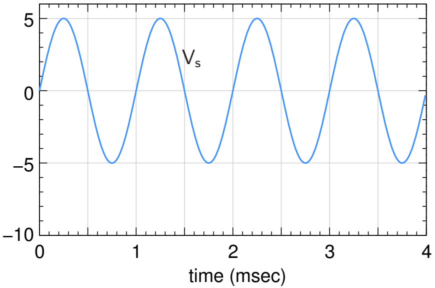

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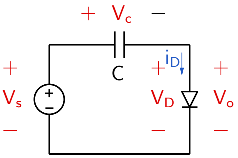
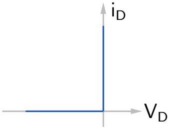
Clamper circuits





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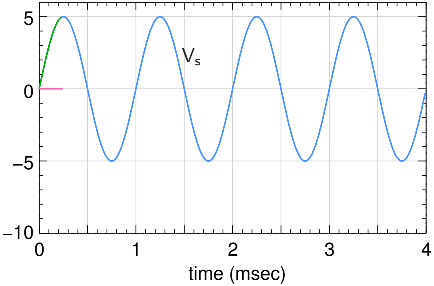

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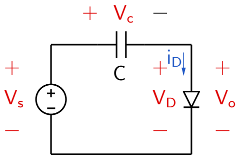

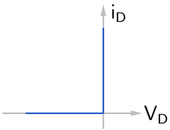

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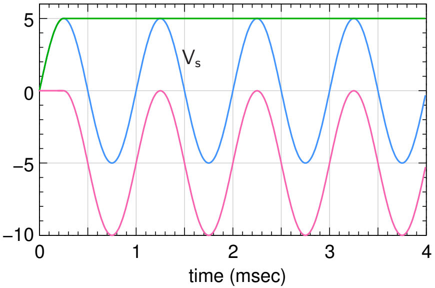

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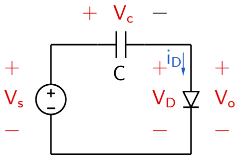

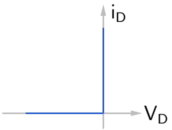

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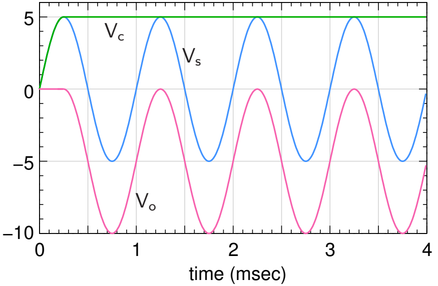

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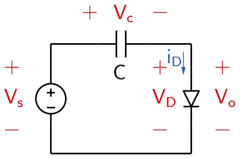
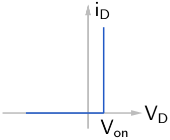
Clamper circuits





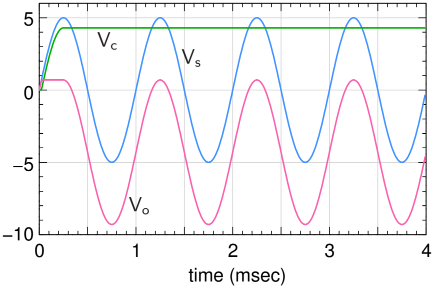
$V_s(t) = V_m \sin \omega t$

$V_c(0) = 0\,V$

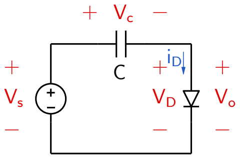
$V_{on} = 0.7\,V$

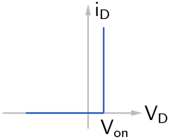
$R_{on} \rightarrow 0\,\Omega$

$R_{off} \rightarrow \infty\,\Omega$



Clamper circuits





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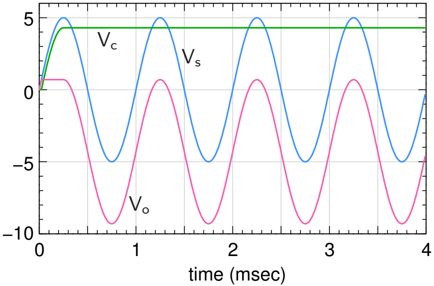
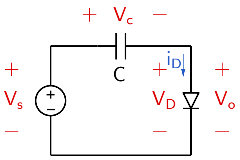
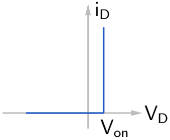


* When D conducts, the capacitor charges instantaneously since R_{on} is small (as in the last circuit). In this phase,
$V_c + V_{on} - V_s = 0 \rightarrow V_c = V_s - V_{on}$.





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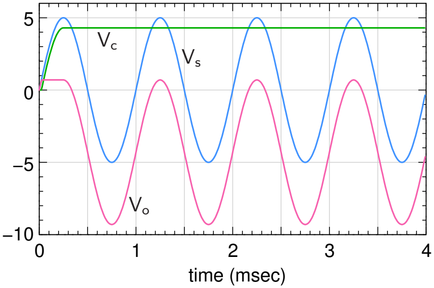

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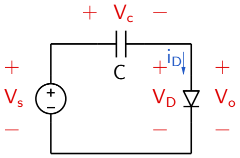

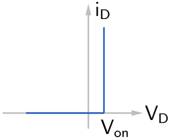

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$R_{on} \rightarrow 0\,\Omega$

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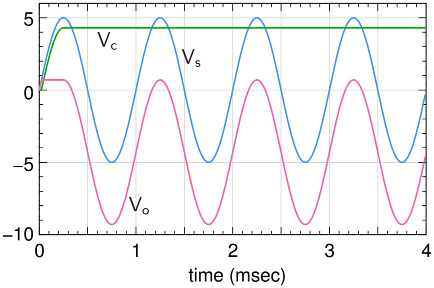

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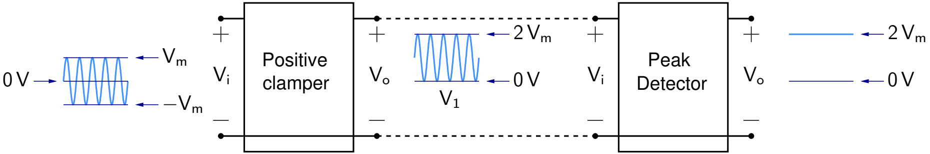
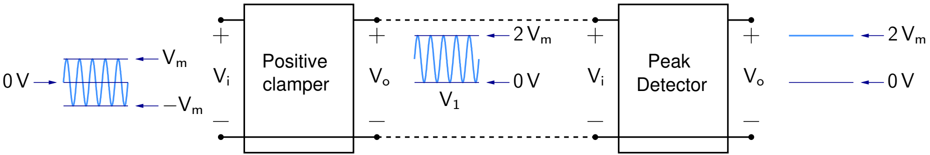
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.
* After V_c reaches its maximum value $(V_m - V_{on})$, it cannot change any more. We then have $V_o(t) = V_s(t) - V_c(t) = V_s(t) - V_m + V_{on}$. In this case, V_o gets clamped at 0.7 V.

Voltage doubler (peak-to-peak detector)

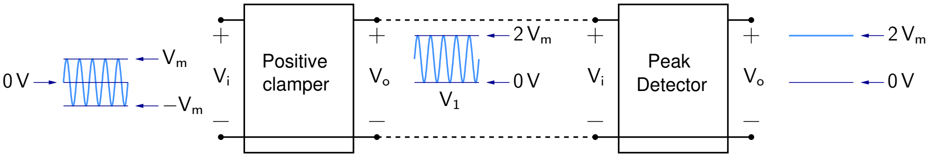


Voltage doubler (peak-to-peak detector)



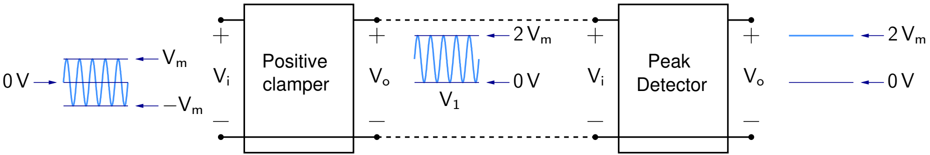
* Input voltage: $-V_m$ to V_m

Voltage doubler (peak-to-peak detector)



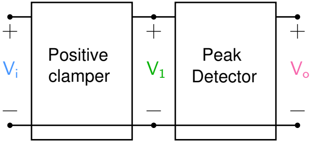
* Input voltage: $-V_m$ to V_m
* Output of positive clamper (V_1): 0 to 2 V_m

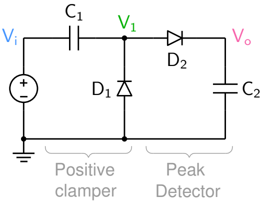
Voltage doubler (peak-to-peak detector)



* Input voltage: $-V_m$ to V_m
* Output of positive clamper (V_1): 0 to 2 V_m
* The peak detector detects the peak of $V_1(t)$, i.e., 2 V_m (dc).

Voltage doubler (peak-to-peak detector)





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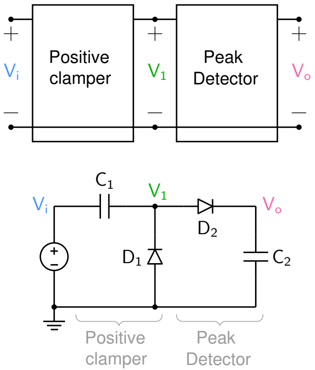
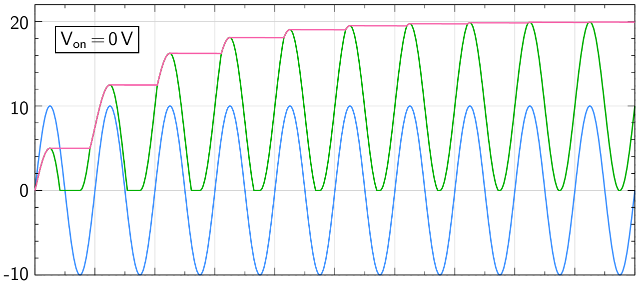
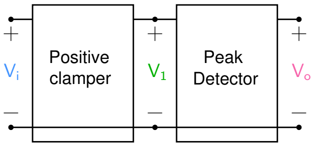
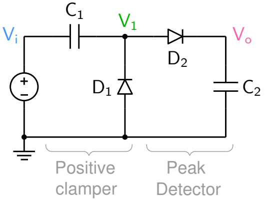
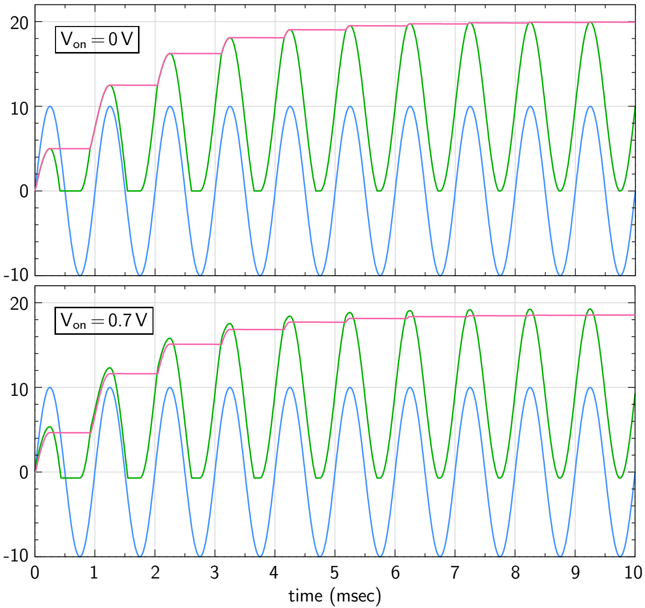




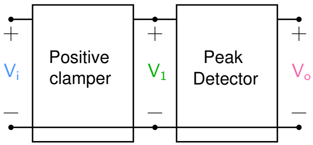
Voltage doubler (peak-to-peak detector)

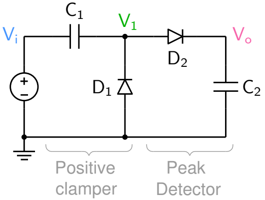






Voltage doubler (peak-to-peak detector)





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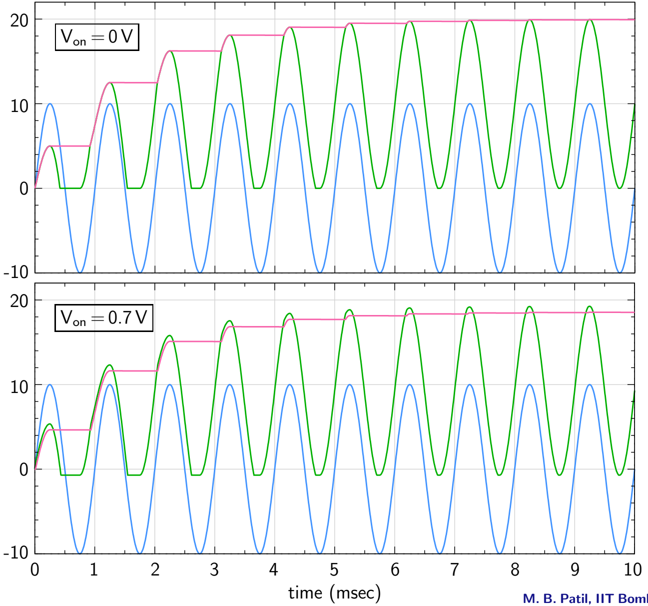
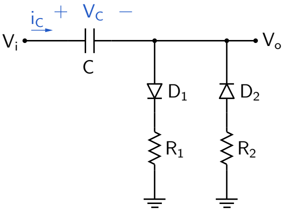
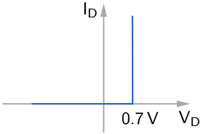
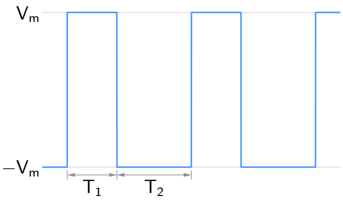


M. B. Patil, IIT Bombay

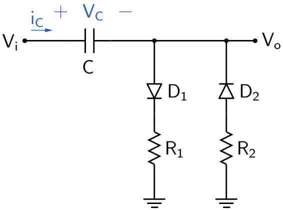
Diode circuit example

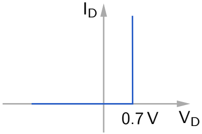


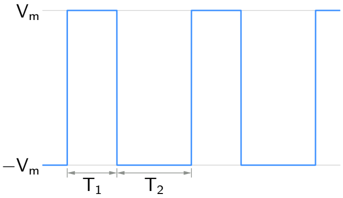




Assuming $R_1 C$ and $R_2 C$ to be large compared to T, find $V_o(t)$ in steady state.



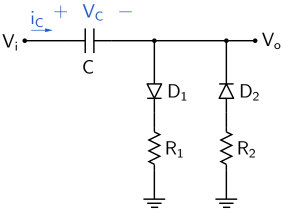


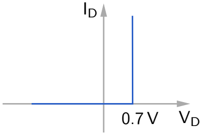


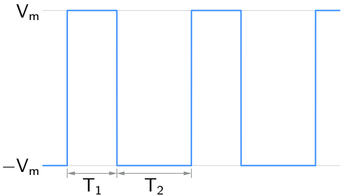
Assuming R_1C and R_2C to be large compared to T, find $V_o(t)$ in steady state.

* Charging time constant $\tau_1 = R_1C$.

Diode circuit example

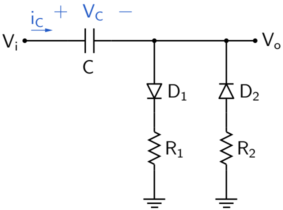


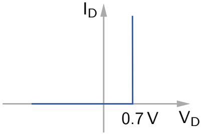


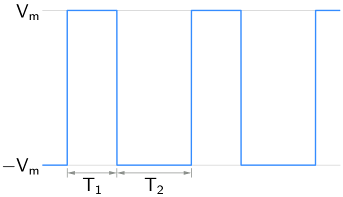


Assuming R_1C and R_2C to be large compared to T, find $V_o(t)$ in steady state.

* Charging time constant $\tau_1 = R_1C$.
* Discharging time constant $\tau_2 = R_2C$.

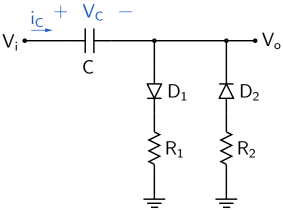


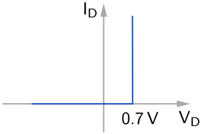


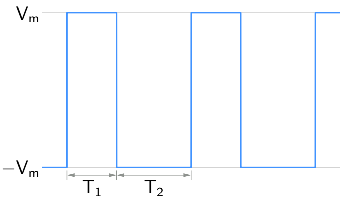


Assuming R_1C and R_2C to be large compared to T, find $V_o(t)$ in steady state.

* Charging time constant $\tau_1 = R_1C$.
* Discharging time constant $\tau_2 = R_2C$.
* Since $\tau_1 \gg T$ and $\tau_2 \gg T$, we expect V_C to be nearly constant in steady state,
  i.e., $V_C(t) \approx \text{constant} \equiv V_C^0$.

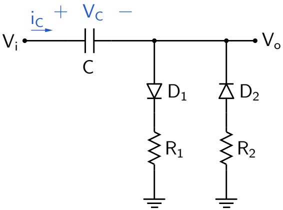


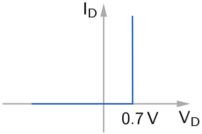


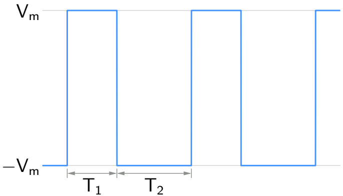


Assuming R_1C and R_2C to be large compared to T, find $V_o(t)$ in steady state.

* Charging time constant $\tau_1 = R_1 C$.
* Discharging time constant $\tau_2 = R_2 C$.
* Since $\tau_1 \gg T$ and $\tau_2 \gg T$, we expect V_C to be nearly constant in steady state,
  i.e., $V_C(t) \approx \text{constant} \equiv V_C^0$.
* $V_o(t) = V_i(t) - V_C(t) \approx V_i(t) - V_C^0$.



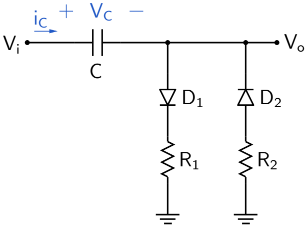




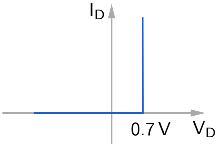
Assuming R_1C and R_2C to be large compared to T, find $V_o(t)$ in steady state.

* Charging time constant $\tau_1 = R_1C$.
* Discharging time constant $\tau_2 = R_2C$.
* Since $\tau_1 \gg T$ and $\tau_2 \gg T$, we expect V_C to be nearly constant in steady state,
  i.e., $V_C(t) \approx \text{constant} \equiv V_C^0$.
* $V_o(t) = V_i(t) - V_C(t) \approx V_i(t) - V_C^0$.

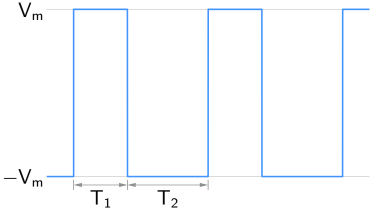
Let us look at an example.



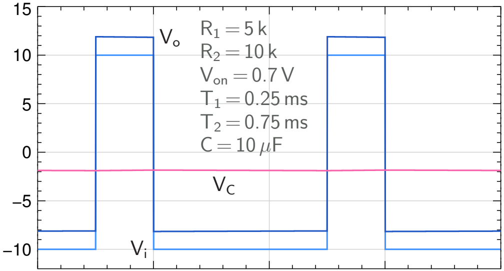
iC
+ VC −
Vi
Vo
C
D1
D2
R1
R2



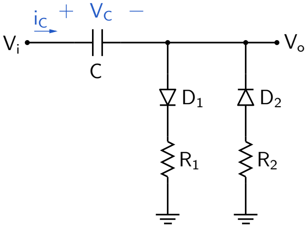
ID
0.7 V
VD

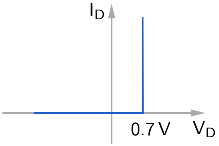


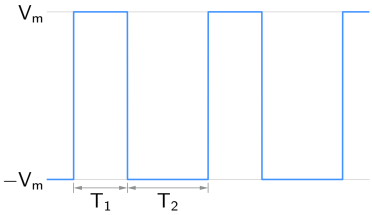
Vm
−Vm
T1
T2

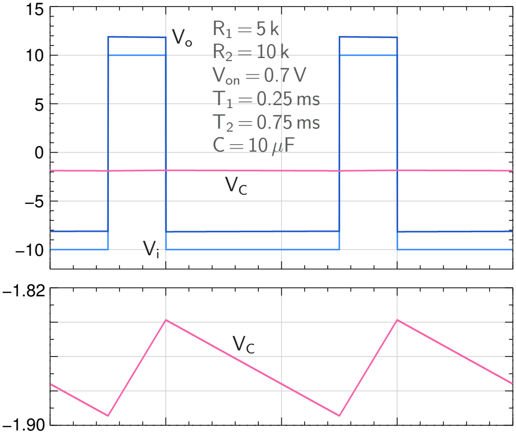


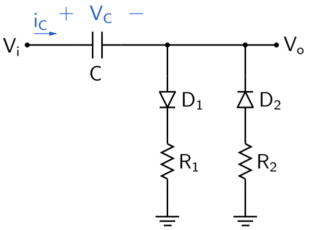
15
10
5
0
−5
−10
Vo
Vi
VC
R1 = 5 k
R2 = 10 k
Von = 0.7 V
T1 = 0.25 ms
T2 = 0.75 ms
C = 10 μF

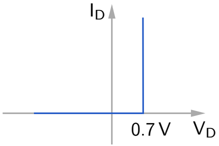

i_C
+ V_C −
V_i
C
V_o
D_1
D_2
R_1
R_2

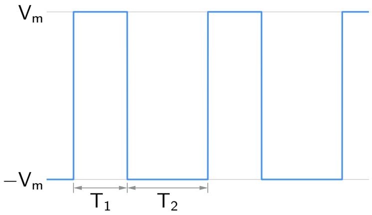

I_D
0.7 V
V_D

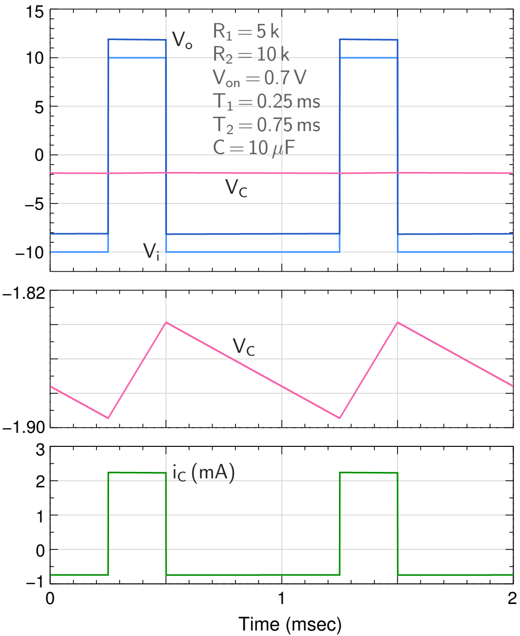

V_m
$-V_m$
T_1
T_2


15
10
5
0
−5
−10
V_o
$R_1 = 5\,k$
$R_2 = 10\,k$
$V_{on} = 0.7\,V$
$T_1 = 0.25\,ms$
$T_2 = 0.75\,ms$
$C = 10\,\mu F$
V_C
V_i
−1.82
−1.90
V_C



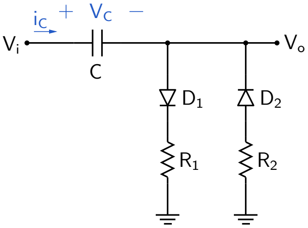


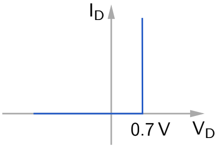


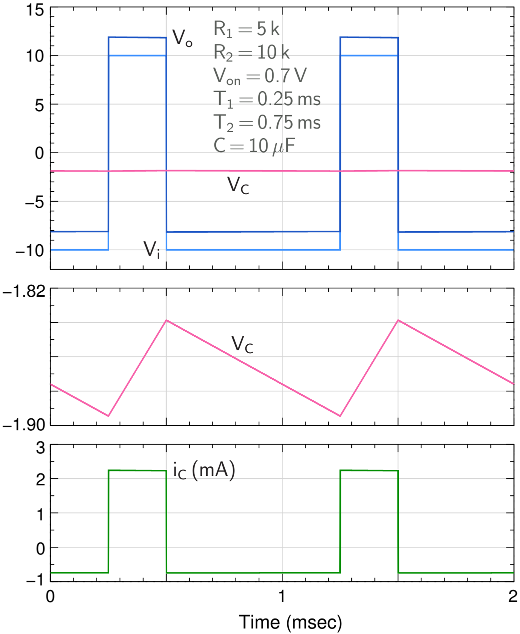


SEQUEL file:

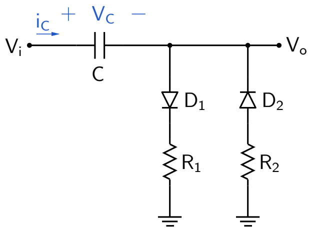
ee101_diode_circuit_13.sqproj

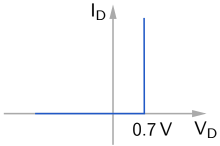


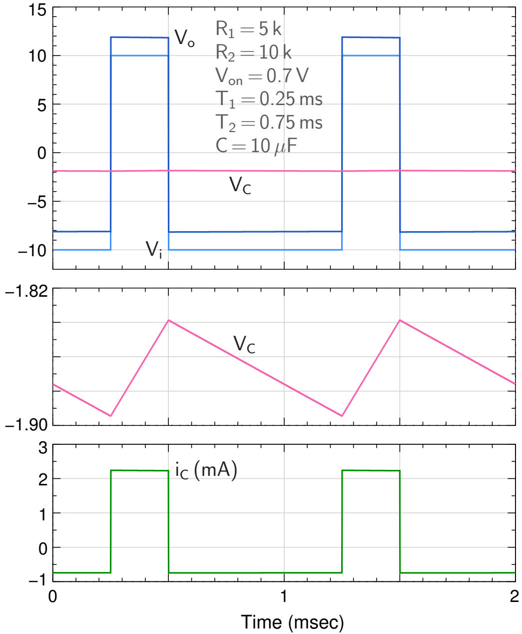




Charge conservation:

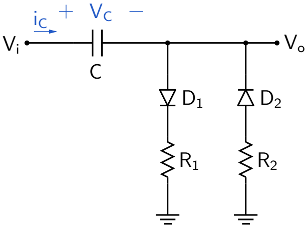


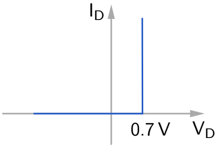




Charge conservation:

$$\Delta Q = \int_0^T i_C\, dt = \int_0^{T_1} i_C\, dt + \int_{T_1}^{T_1+T_2} i_C\, dt = 0.$$





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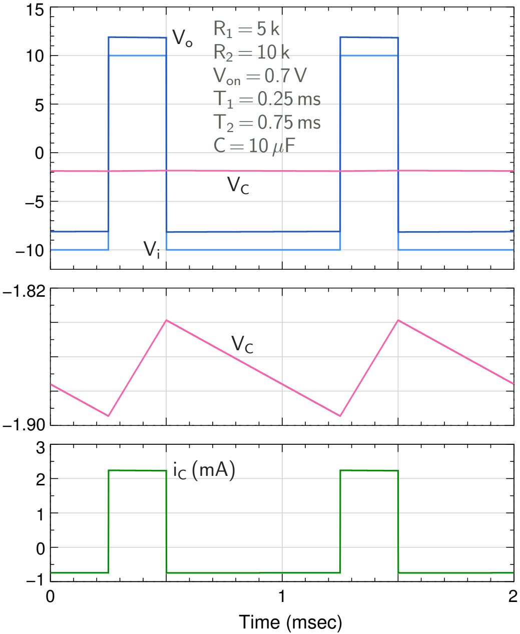
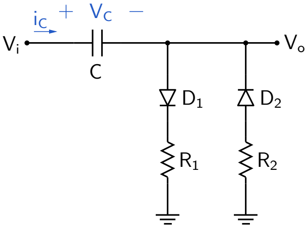
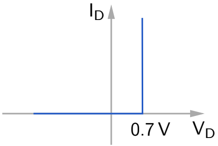
$$T_1 \left(\frac{V_m - V_C - V_{on}}{R_1} \right) - T_2 \left(\frac{0 - (-V_m - V_C) - V_{on}}{R_2} \right) = 0.$$







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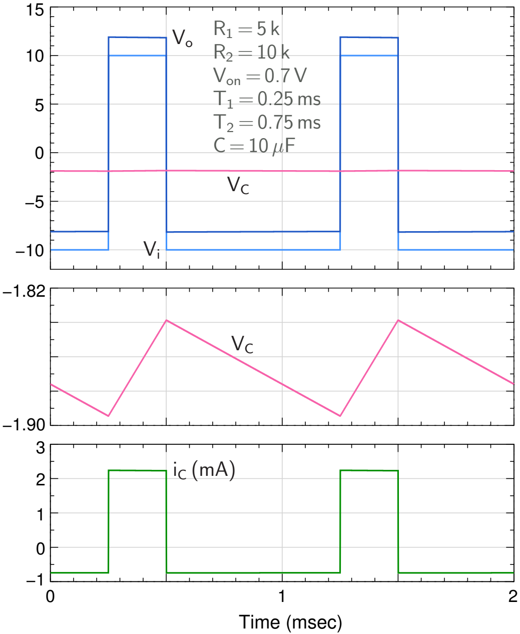
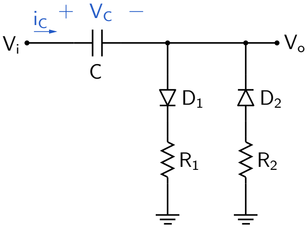
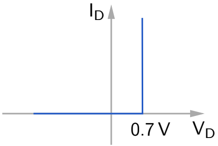
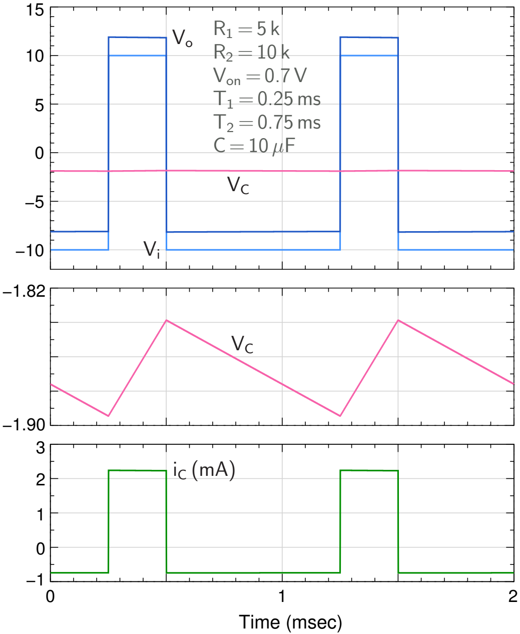
$$\left(\frac{T_1}{R_1} - \frac{T_2}{R_2} \right) (V_m - V_{on}) = V_C \left(\frac{T_1}{R_1} + \frac{T_2}{R_2} \right).$$









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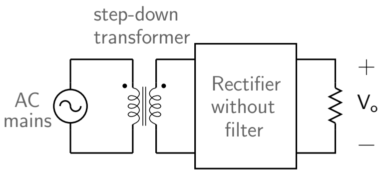
$$\rightarrow V_C = \frac{\left(\frac{T_1}{R_1} - \frac{T_2}{R_2} \right)}{\left(\frac{T_1}{R_1} + \frac{T_2}{R_2} \right)} (V_m - V_{on}) = -1.86\,\text{V}.$$

* A rectifier is used to convert an AC voltage to a DC voltage (typically 5 to 20 V), e.g., a mobile phone charger.

Rectifiers

* A rectifier is used to convert an AC voltage to a DC voltage (typically 5 to 20 V), e.g., a mobile phone charger.
* AC mains $\rightarrow$ step-down transformer $\rightarrow$ DC voltage OR
  AC mains $\rightarrow$ DC voltage $\rightarrow$ lower DC voltage



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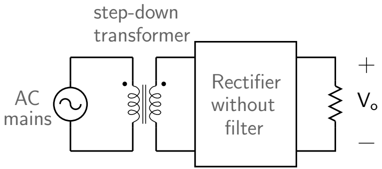
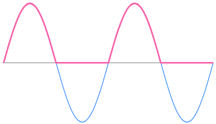
Rectifiers





half-wave rectifier

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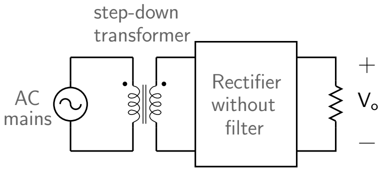
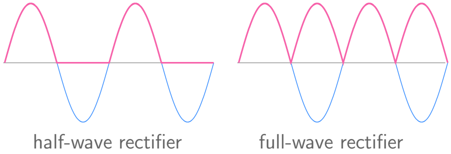
Rectifiers





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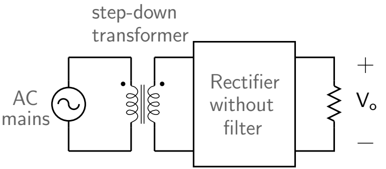
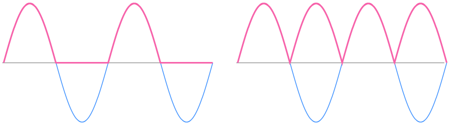
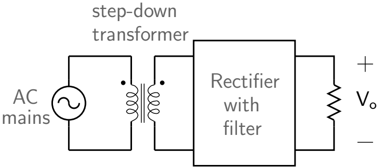
Rectifiers



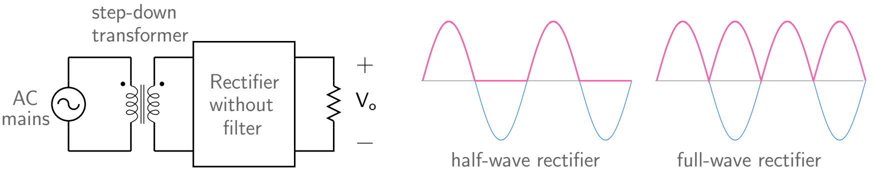


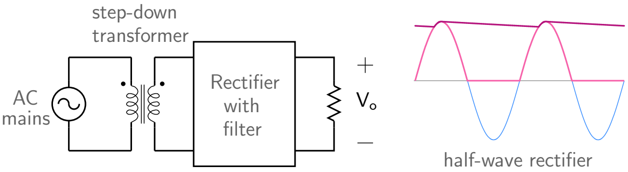
half-wave rectifier   full-wave rectifier



- A rectifier is used to convert an AC voltage to a DC voltage (typically 5 to 20 V), e.g., a mobile phone charger.
- AC mains → step-down transformer → DC voltage OR
  AC mains → DC voltage → lower DC voltage

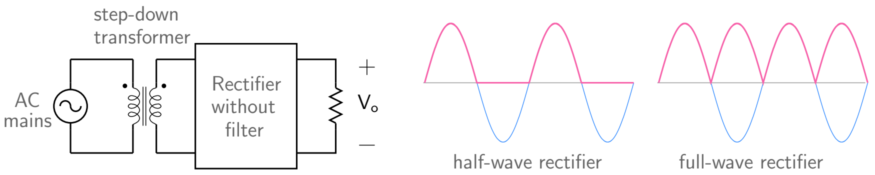
Rectifiers

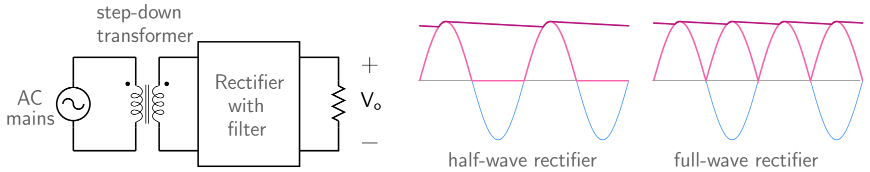




* A rectifier is used to convert an AC voltage to a DC voltage (typically 5 to 20 V), e.g., a mobile phone charger.
* AC mains → step-down transformer → DC voltage OR
  AC mains → DC voltage → lower DC voltage

Rectifiers





* A rectifier is used to convert an AC voltage to a DC voltage (typically 5 to 20 V), e.g., a mobile phone charger.
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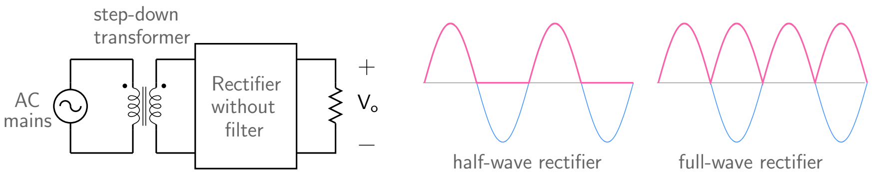
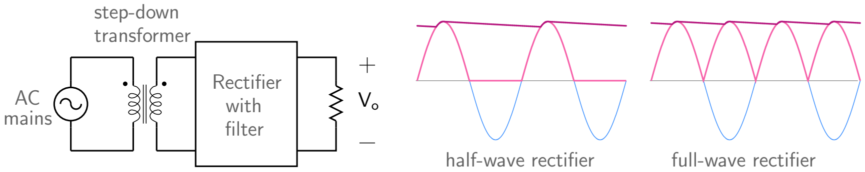
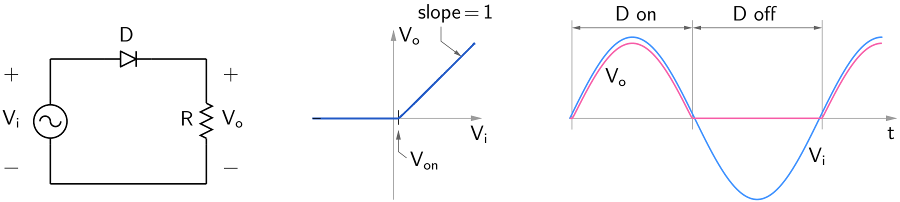
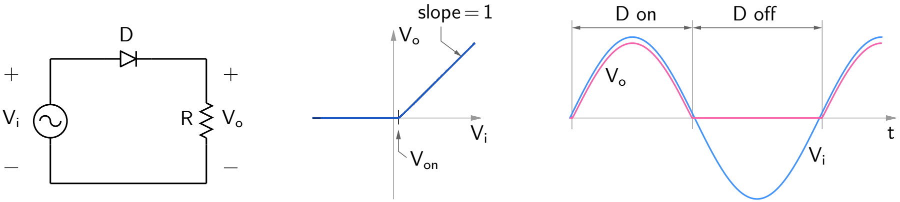
Rectifiers





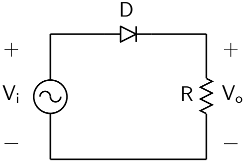
* A rectifier is used to convert an AC voltage to a DC voltage (typically 5 to 20 V), e.g., a mobile phone charger.
* AC mains → step-down transformer → DC voltage OR
  AC mains → DC voltage → lower DC voltage
* A voltage regulator would be typically used to remove the ripple riding on the DC output.

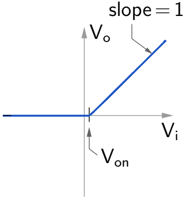

D
+
+
V_i
R
V_o
−
−
slope = 1
V_o
V_i
V_on
D on
D off
V_o
t
V_i

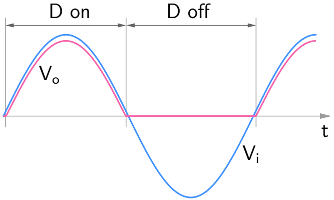


* D conducts only if $V_i > V_{\rm on}$, and in that case $V_o = V_i - V_{\rm on}$, a straight line with slope = 1.

Half-wave rectifier without filter

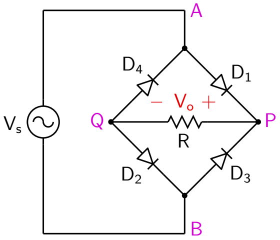




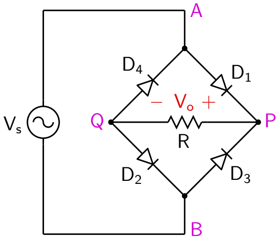


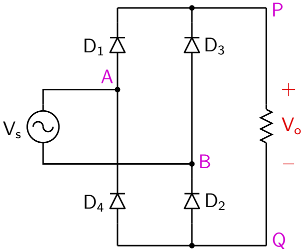
* D conducts only if $V_i > V_{\rm on}$, and in that case $V_o = V_i - V_{\rm on}$, a straight line with slope = 1.
* If $V_i < V_{\rm on}$, D does not conduct $\rightarrow$ $V_o = 0$.

Full-wave (bridge) rectifier without filter

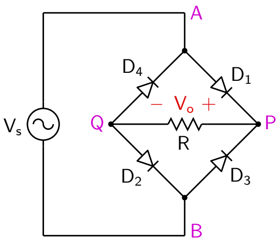


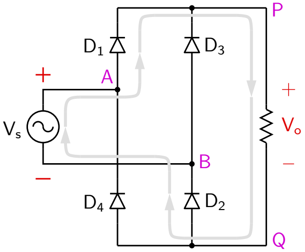
Full-wave (bridge) rectifier without filter



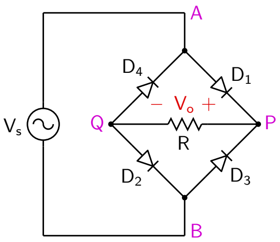


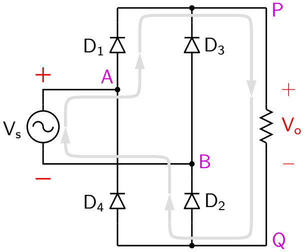
Full-wave (bridge) rectifier without filter

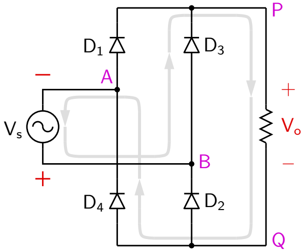




Full-wave (bridge) rectifier without filter







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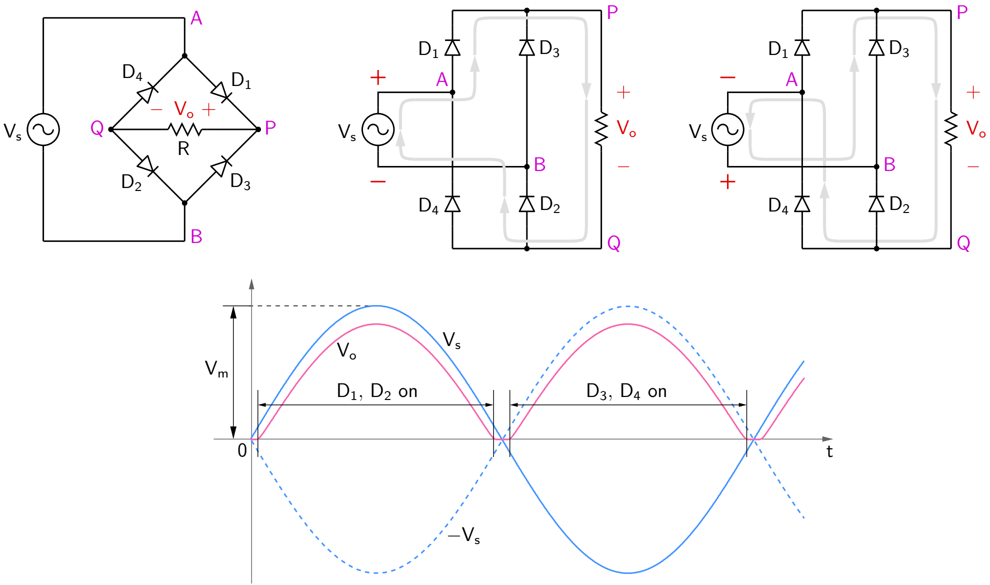
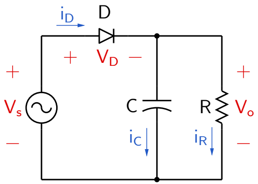
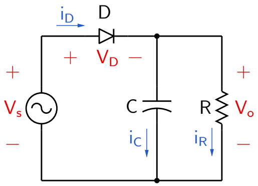


Half-wave rectifier with capacitor filter

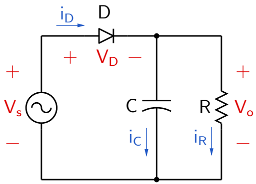


Half-wave rectifier with capacitor filter



* Similar to the peak detector except that the load resistance provides a discharge path for the capacitor in this case.

Half-wave rectifier with capacitor filter



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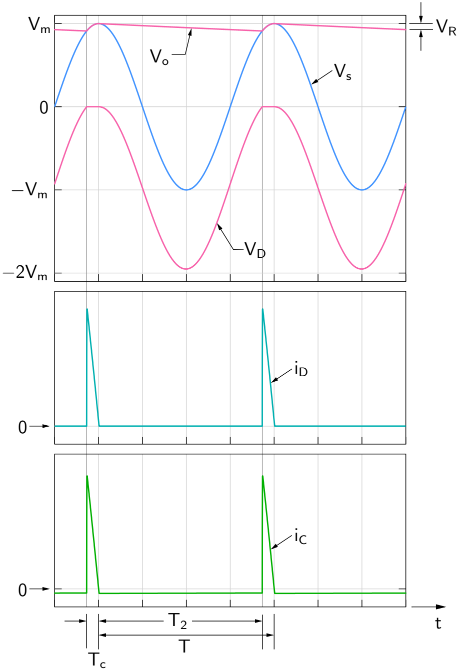
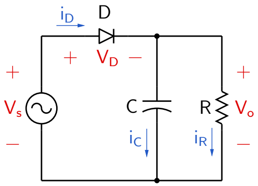


Half-wave rectifier with capacitor filter



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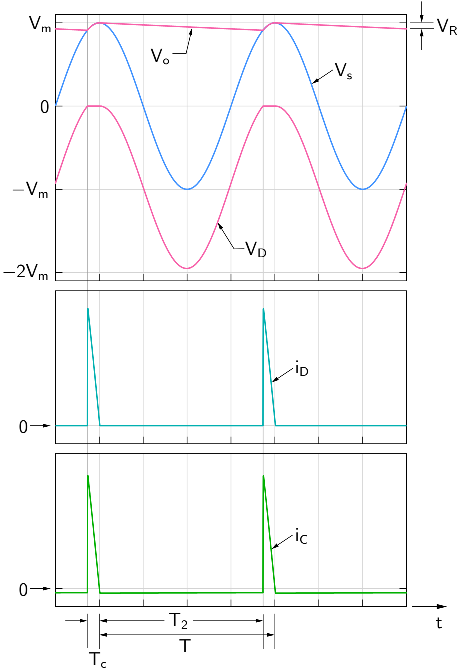
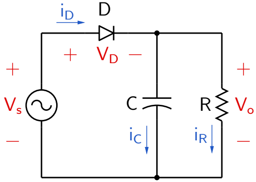
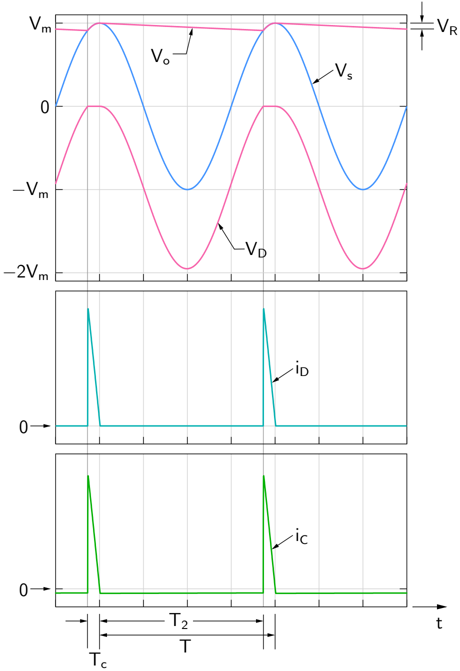


Half-wave rectifier with capacitor filter





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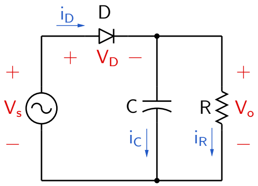
- The peak diode current is much larger than the average load current.

Half-wave rectifier with capacitor filter



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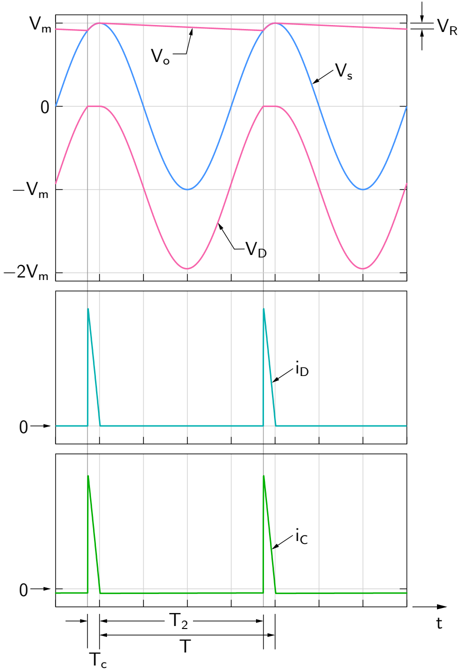
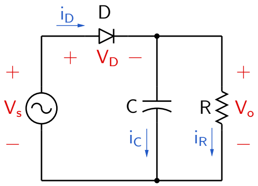
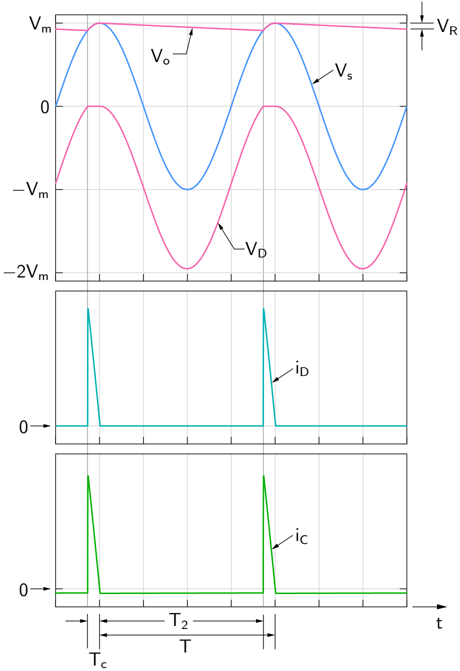
- $V_D(t) = V_s(t) - V_o(t) \approx V_s(t) - V_m$
  → The maximum reverse bias ("Peak Inverse Voltage" or PIV) across the diode is 2 V_m.



Half-wave rectifier with capacitor filter





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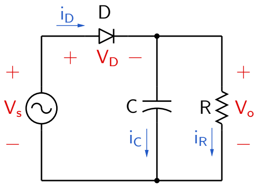
* With $V_{on} = 0.7\,\mathrm{V}$, the plots are slightly different.

Half-wave rectifier with capacitor filter



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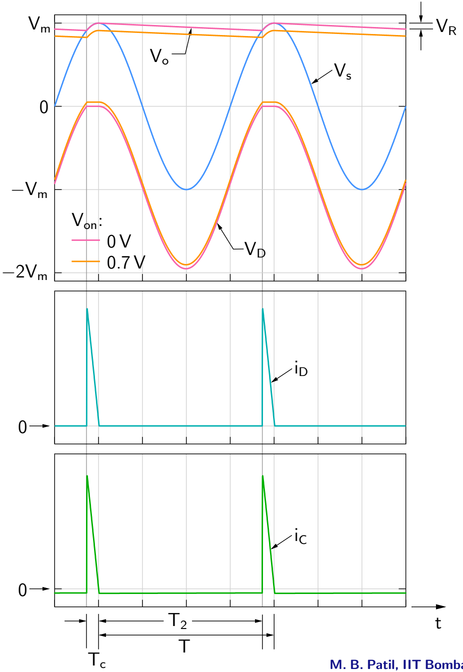
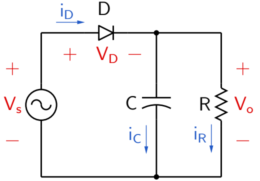
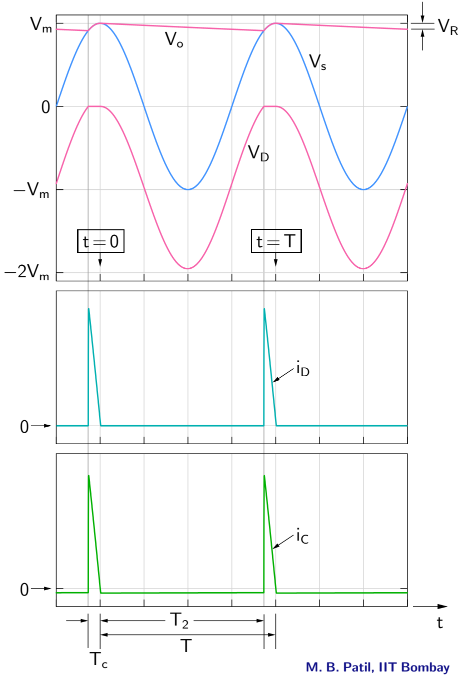


Half-wave rectifier with capacitor filter



$V_m = 16\,\text{V}$, $f = 50\,\text{Hz}$, $R = 100\,\Omega$. For a ripple voltage $V_R = 2\,\text{V}$, find (a) the filter capacitance C, (b) average and peak diode currents, (c) maximum reverse voltage across the diode.
(Let $V_{on} = 0\,\text{V}$.)



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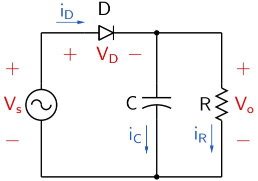
Half-wave rectifier with capacitor filter



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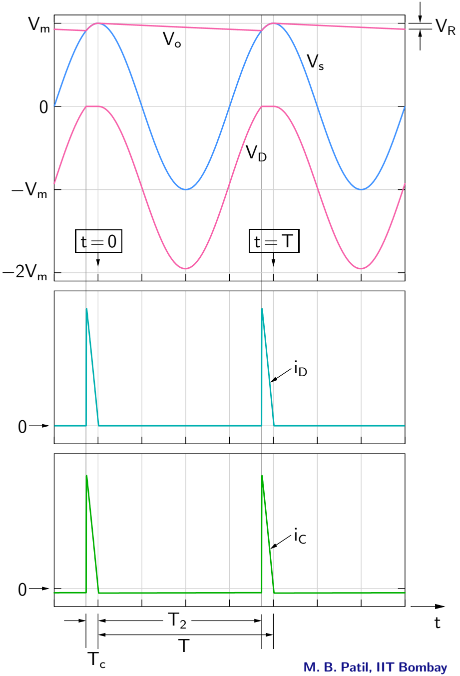
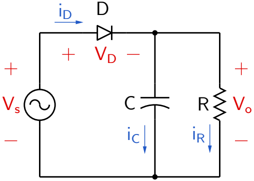
(a) Filter Capacitance

1. In the discharge phase,

$$V_o(t) = V_m e^{-t/\tau} \approx V_m \left(1 - \frac{t}{\tau}\right).$$



Half-wave rectifier with capacitor filter



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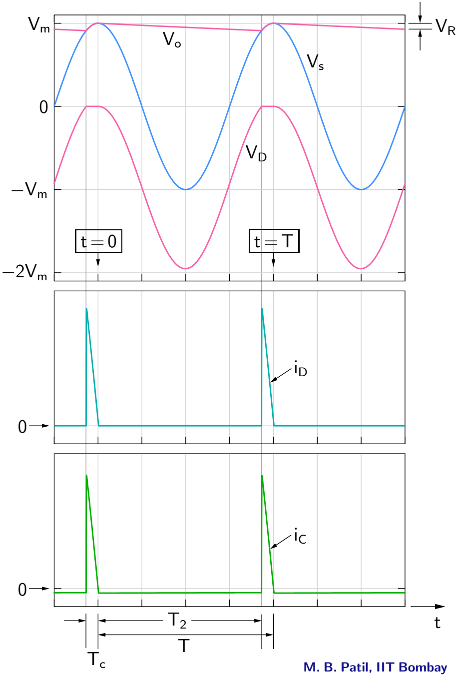
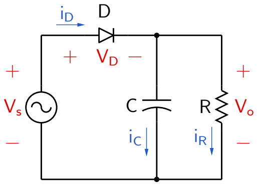
The drop in $V_o(t)$ is given by the second term.

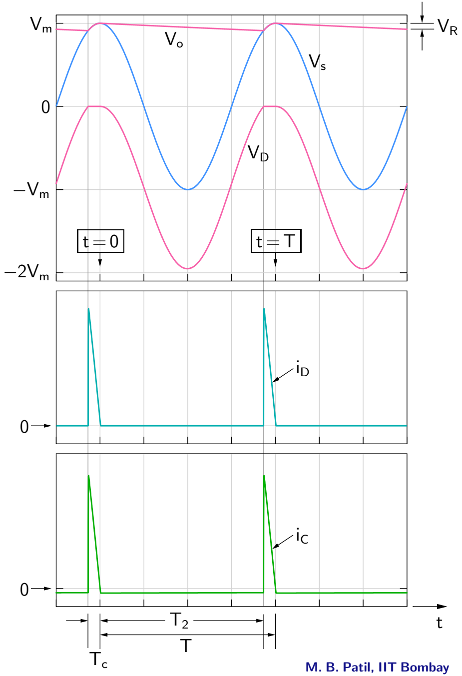
Using $T_2 \approx T$,

$$V_R = V_m \frac{T}{\tau} = V_m \frac{T}{RC}.$$

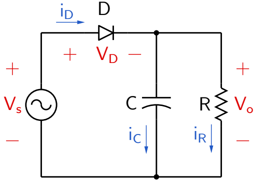


Half-wave rectifier with capacitor filter





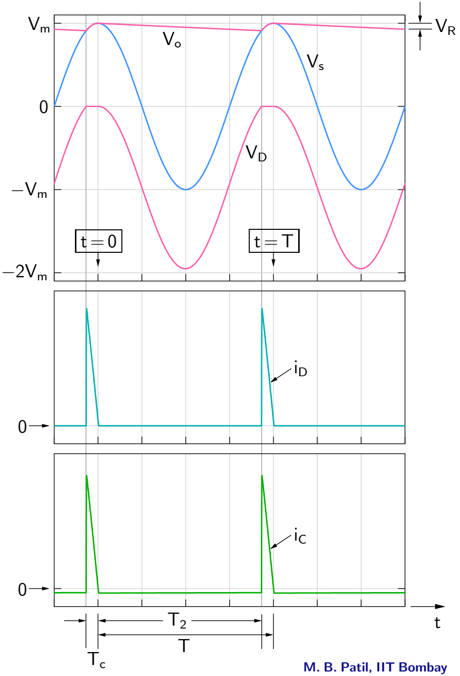
Half-wave rectifier with capacitor filter



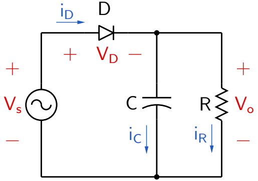
(a) Filter capacitance

2. Assuming $i_C = i_R = \frac{V_o}{R} \approx \frac{V_m}{R}$ in the discharge phase, we get

$$i_C = \frac{V_m}{R} = C\,\frac{\Delta V_o}{\Delta t} \approx C\,\frac{V_R}{T} \rightarrow V_R = V_m\,\frac{T}{RC}.$$



Half-wave rectifier with capacitor filter



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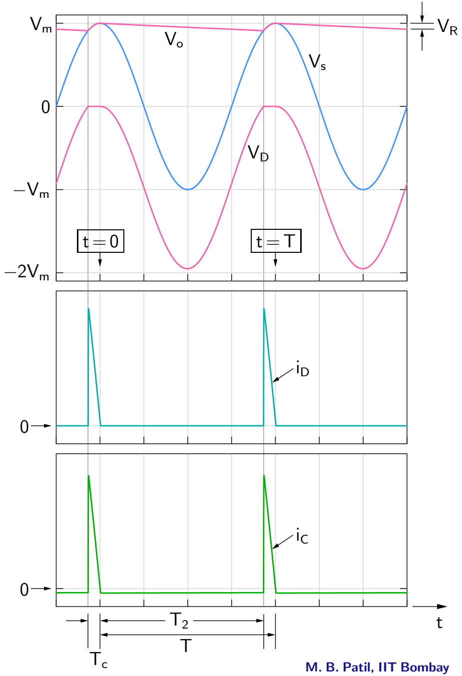
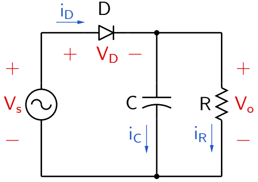
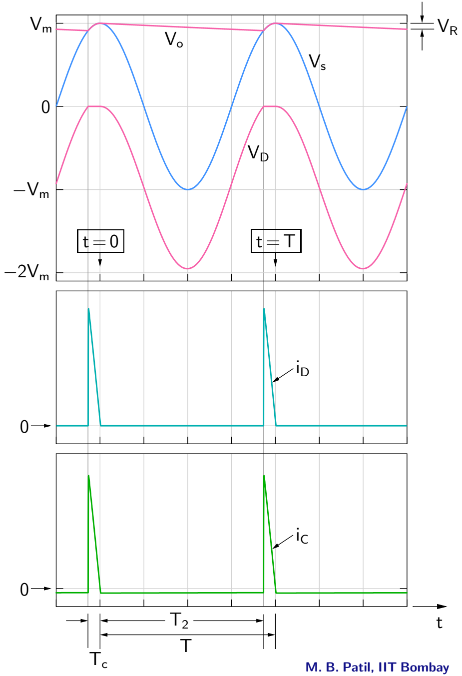
$$\rightarrow C = \frac{V_m}{V_R}\,\frac{T}{R} = \frac{16\,\text{V}}{2\,\text{V}}\,\frac{20\,\text{ms}}{100\,\Omega} = 1600\,\mu\text{F}.$$



Half-wave rectifier with capacitor filter



(b) Average diode current



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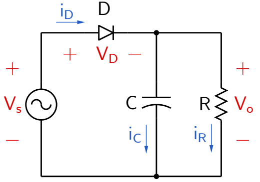
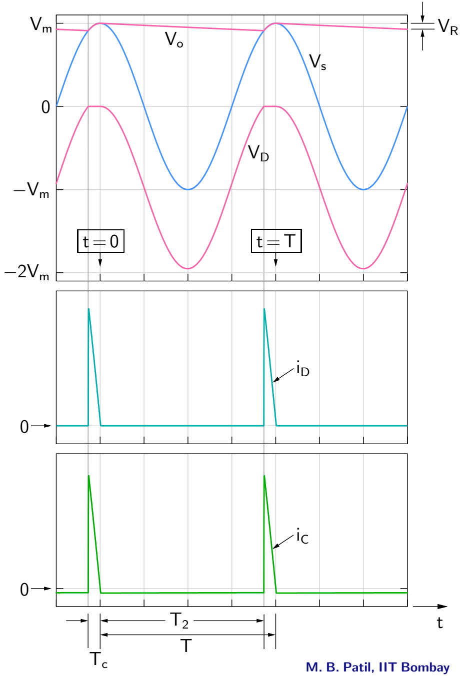


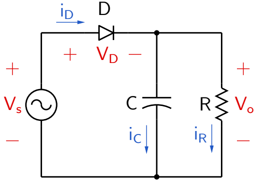
(b) Average diode current

Using charge balance,

$$\int_{T-T_c}^{T} (i_D - i_R)\, dt = \int_{0}^{T-T_c} i_R\, dt$$



Half-wave rectifier with capacitor filter



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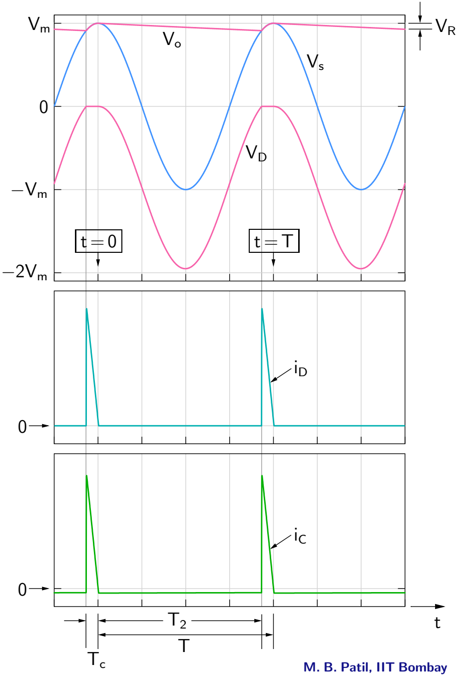
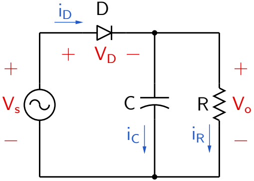


Half-wave rectifier with capacitor filter



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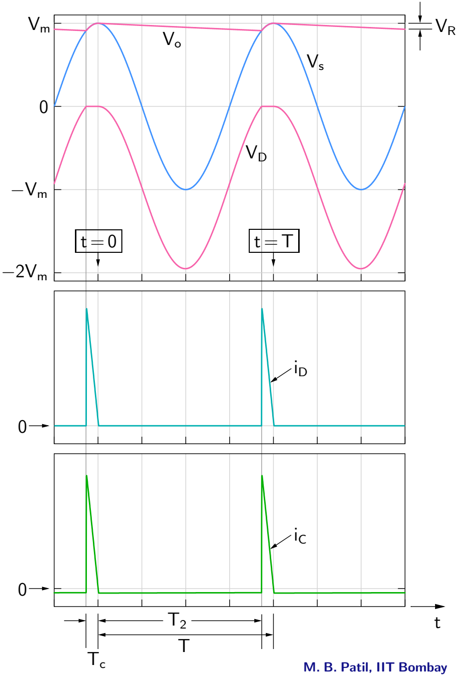
$$\rightarrow \int_{T-T_c}^{T} i_D\, dt = \int_0^{T} i_R\, dt.$$

$$i_D^{av} = \frac{1}{T}\int_0^{T} i_D\, dt = \frac{1}{T}\int_{T-T_c}^{T} i_D\, dt$$

$$= \frac{1}{T}\int_0^{T} i_R\, dt \approx \frac{V_m}{R}.$$



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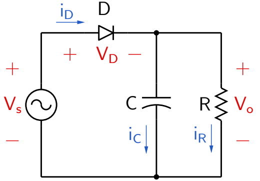
Half-wave rectifier with capacitor filter



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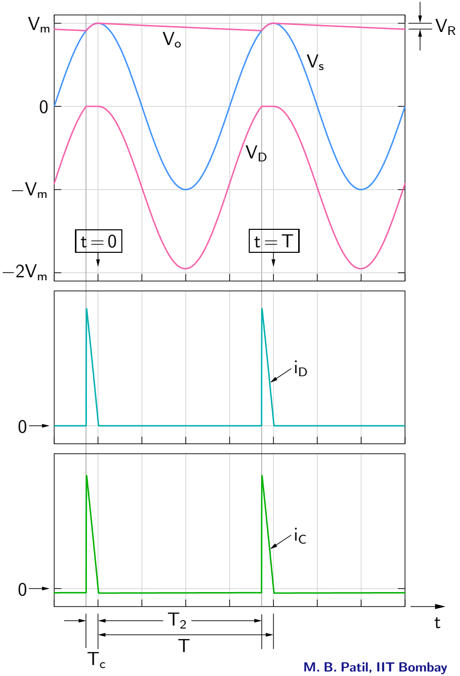
$$i_D^{av} \approx \frac{16\,\text{V}}{100\,\Omega} = 160\,\text{mA}.$$



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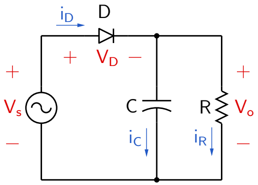
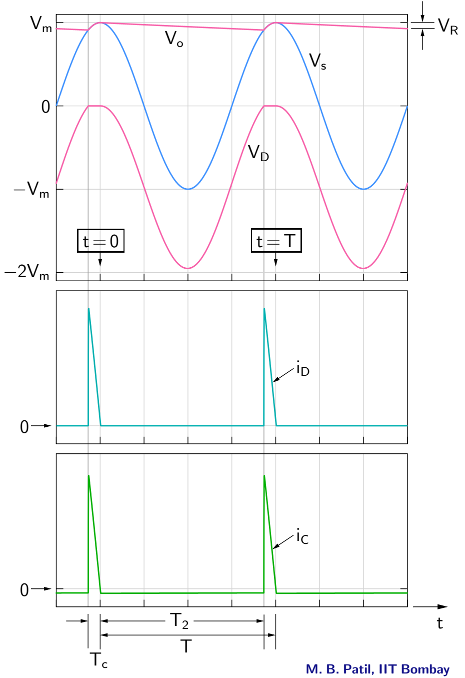
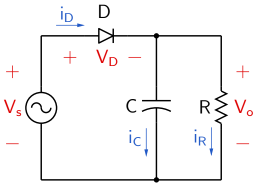


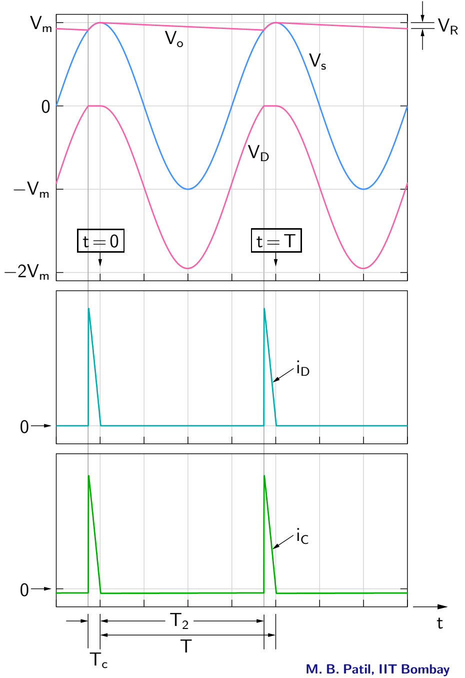
(b) Peak diode current

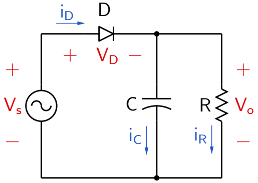




(b) Peak diode current

$$i_D^{\text{peak}} = C\,\frac{d}{dt}\,(V_m \cos\omega t)\Big|_{t=-T_c} + \frac{V_m}{R}$$





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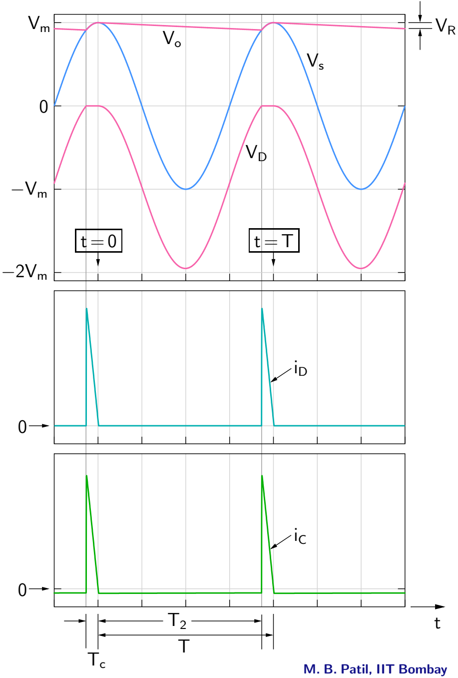
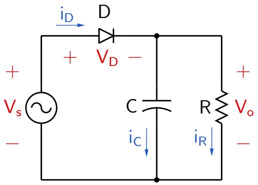
$$= -\omega C\, V_m \sin(-\omega T_c) + \frac{16\,\text{V}}{100\,\Omega}$$

$$= \omega C\, V_m \sin\omega T_c + 0.16$$





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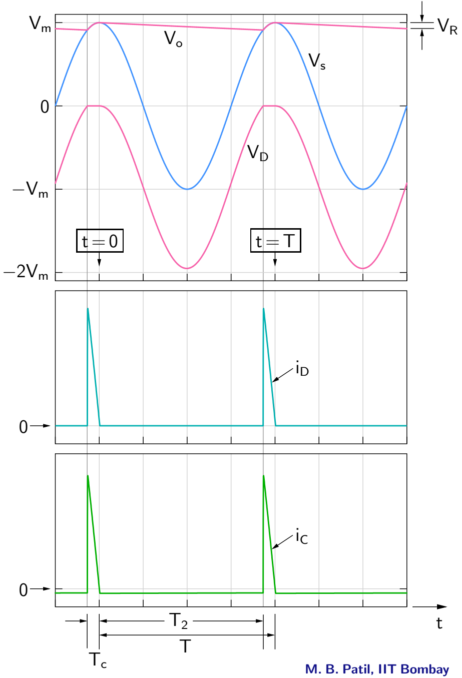
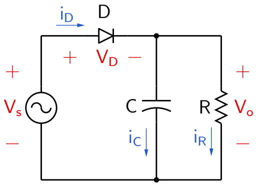
$V_m\, \cos(-\omega T_c) = V_m - V_R,$ giving

$$\omega T_c = \cos^{-1}\left(1 - \frac{V_R}{V_m}\right) = \cos^{-1}\left(1 - \frac{2}{16}\right) = 29^\circ.$$





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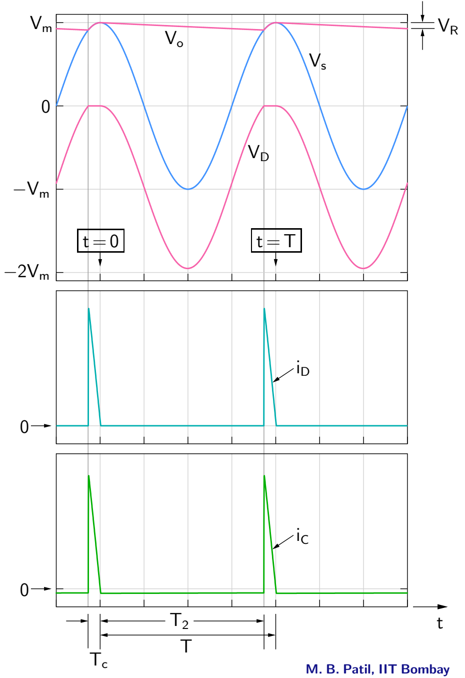
$$i_D^{\text{peak}} = 2\pi \times 50 \times 1600 \times 10^{-6} \times 16 \times \sin 29^\circ + 0.16$$

$$= 3.89 + 0.16 = 4.05\ \text{A}.$$



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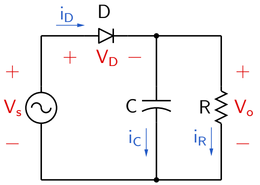
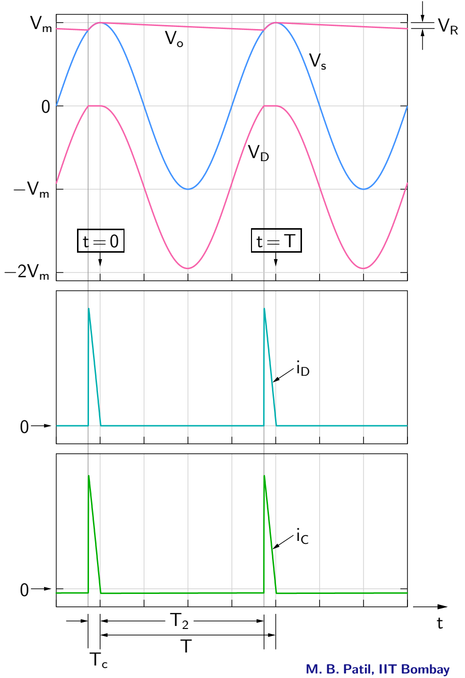
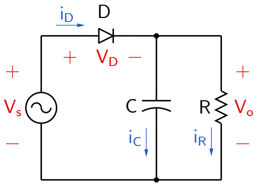


(b) Peak diode current: analytic expression





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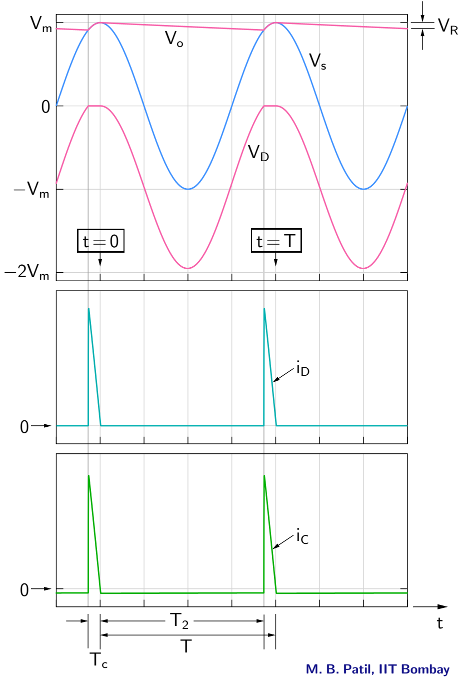
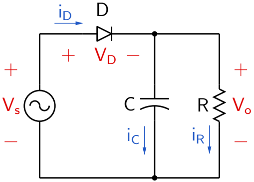
$$V_m \cos(-\omega T_c) = V_m - V_R \rightarrow \cos \omega T_c = 1 - \frac{V_R}{V_m} \equiv 1 - x$$





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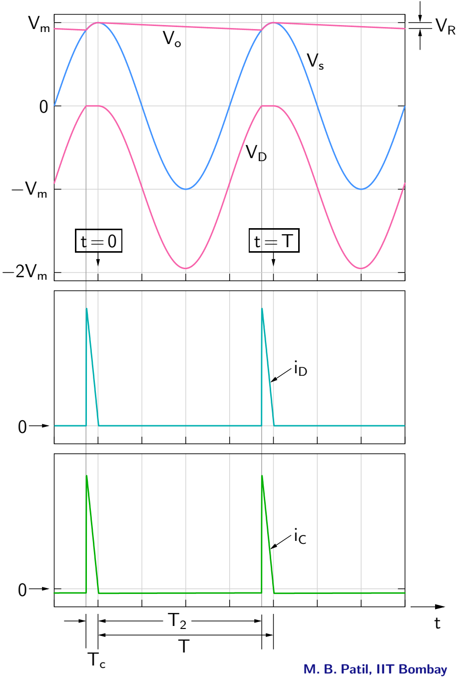

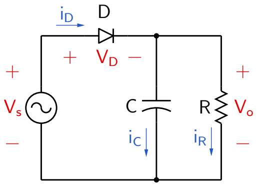

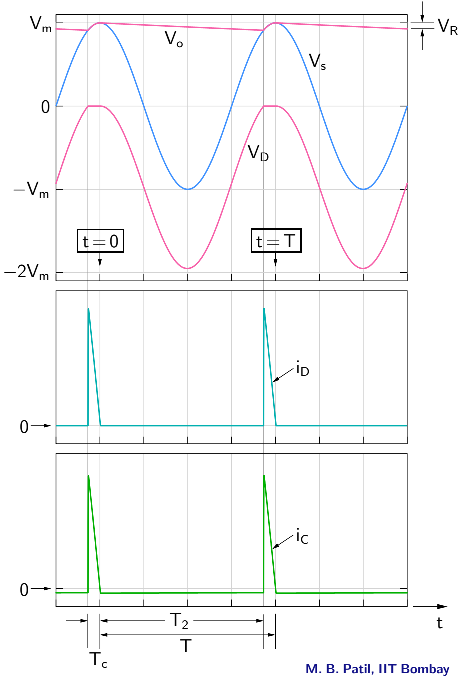

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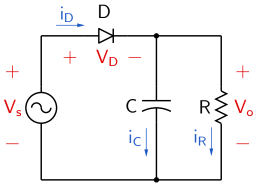

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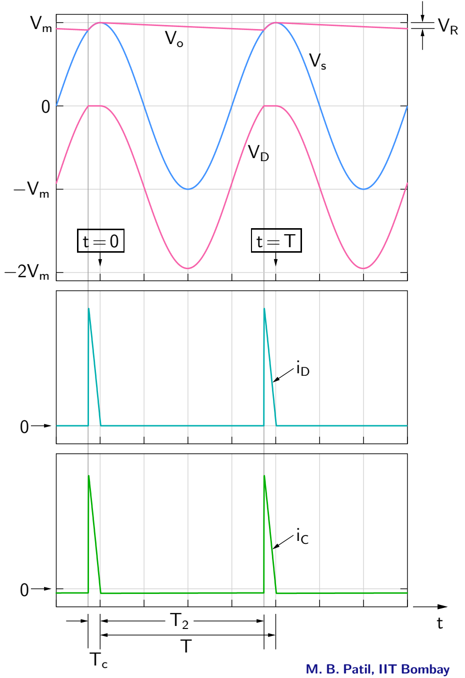
(c) Maximum reverse bias $\approx 2\,V_m = 32\,\text{V}$.



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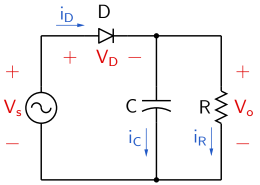

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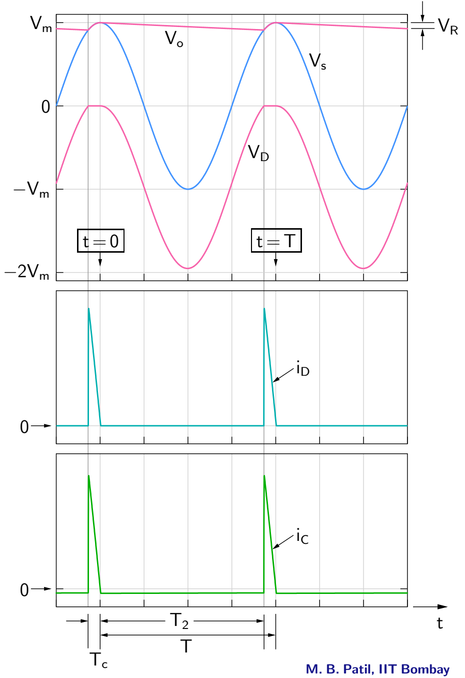
SEQUEL file: `ee101_half_rectifier.sqproj`



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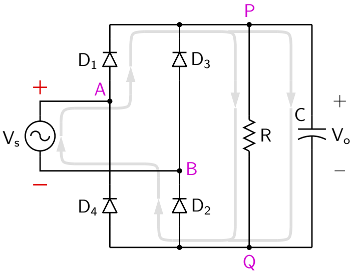
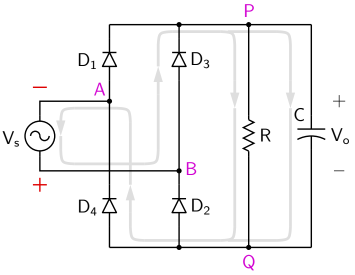
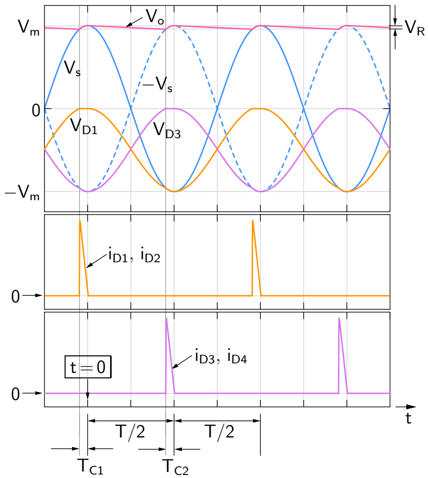
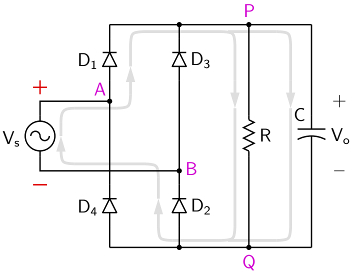
Full-wave (bridge) rectifier with capacitor filter

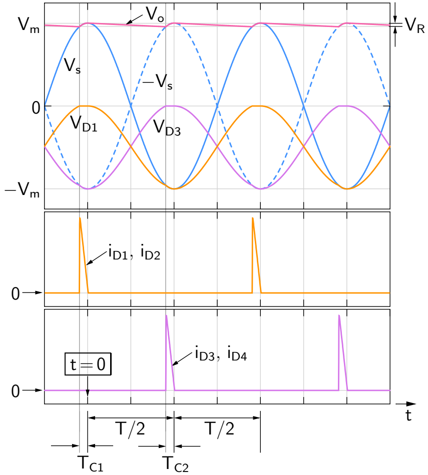






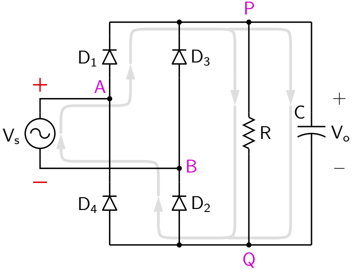
Full-wave (bridge) rectifier with capacitor filter

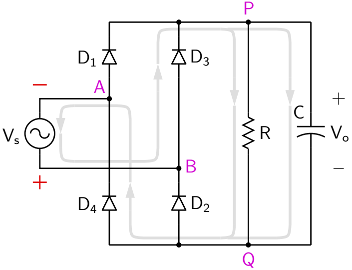


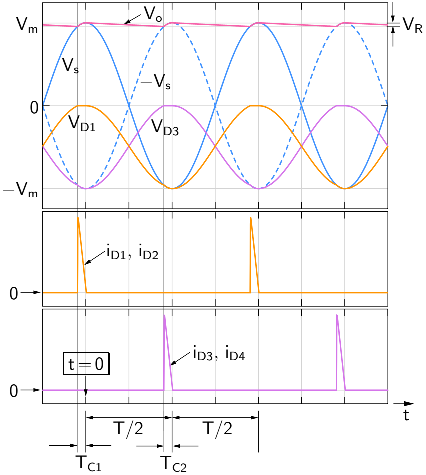


* As in the half-wave rectifier case, we have charging and discharging intervals, and $V_o \approx V_m$ is maintained.

Full-wave (bridge) rectifier with capacitor filter







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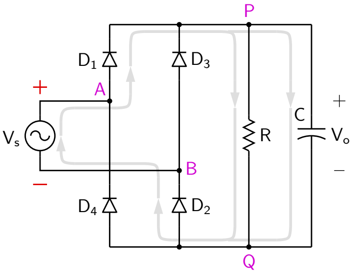
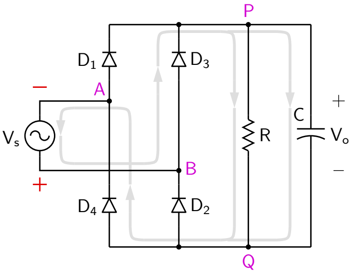
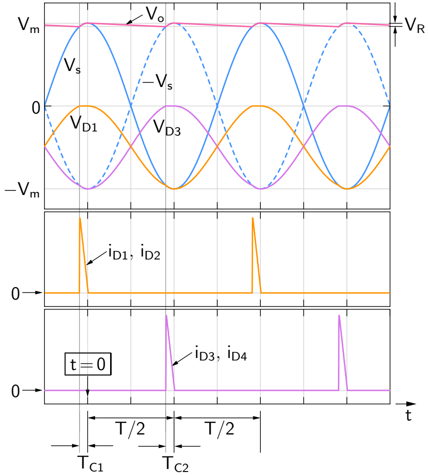
Full-wave (bridge) rectifier with capacitor filter







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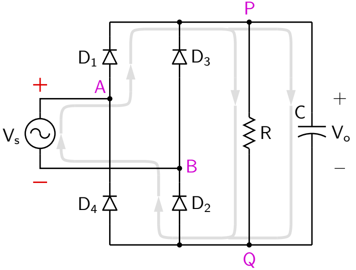

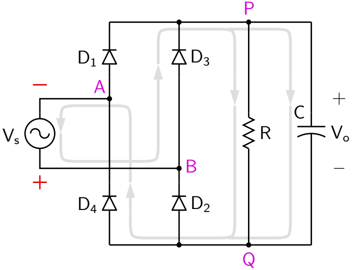

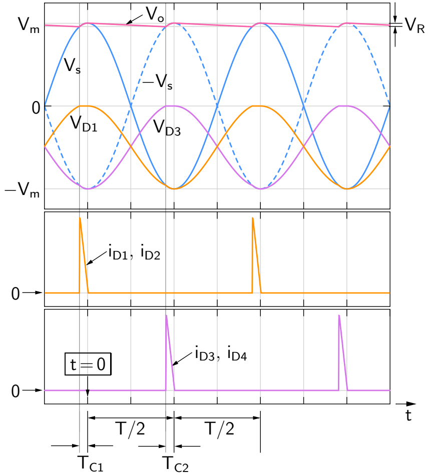

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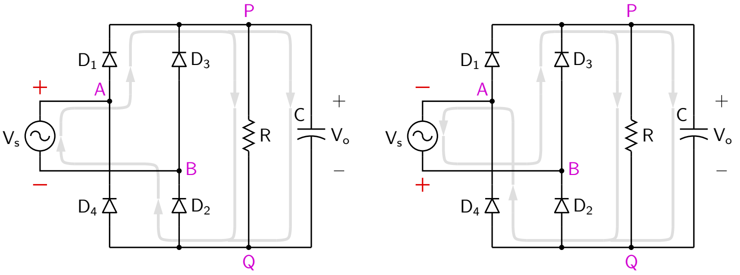
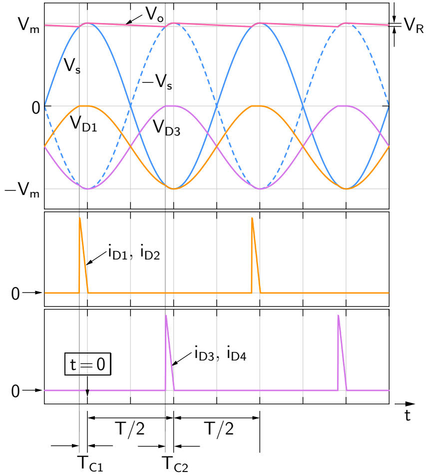
- The discharging interval is typically much longer than the charging intervals (T_{C1} and T_{C2}).

Full-wave (bridge) rectifier with capacitor filter





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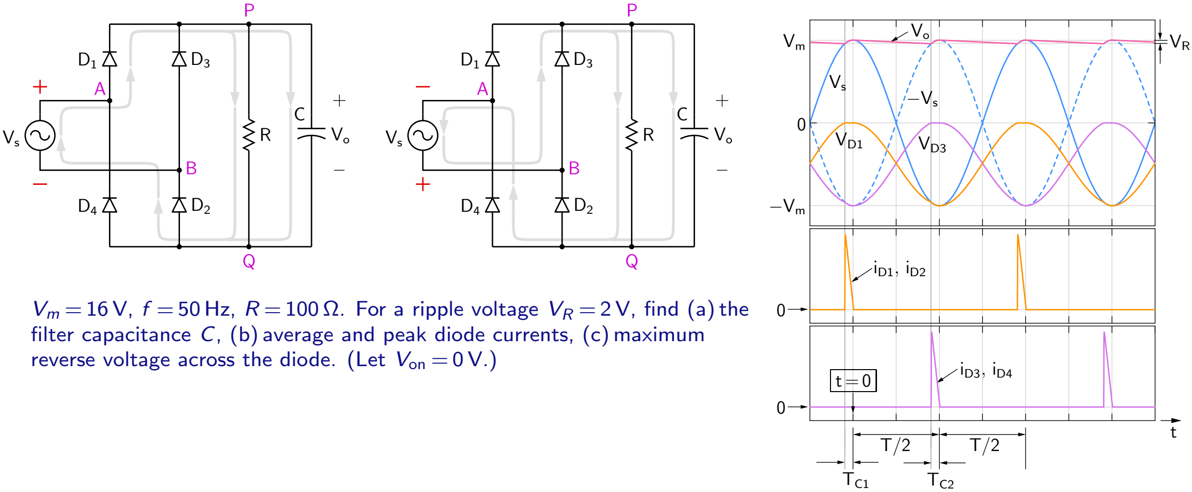
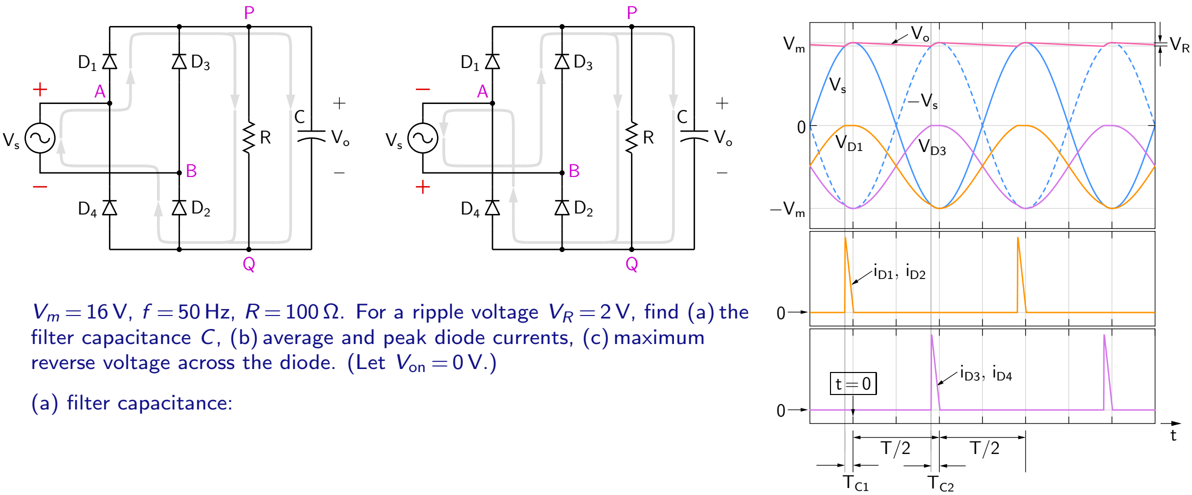
* The maximum reverse bias across any of the diodes is V_m.

Full-wave rectifier with capacitor filter



$V_m = 16\,\text{V}$, $f = 50\,\text{Hz}$, $R = 100\,\Omega$. For a ripple voltage $V_R = 2\,\text{V}$, find (a) the filter capacitance C, (b) average and peak diode currents, (c) maximum reverse voltage across the diode. (Let $V_{on} = 0\,\text{V}$.)

Full-wave rectifier with capacitor filter



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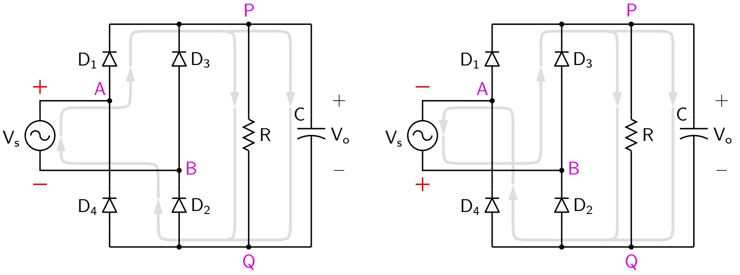

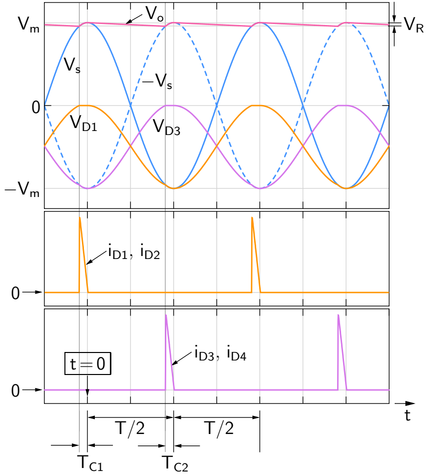

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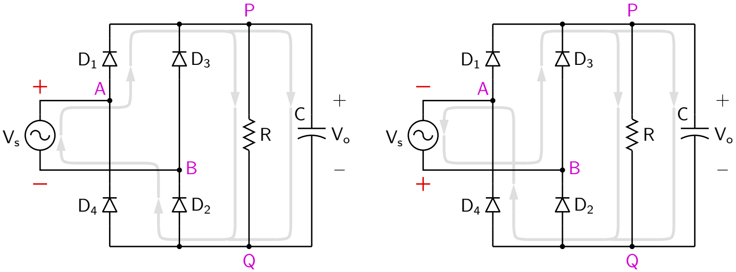
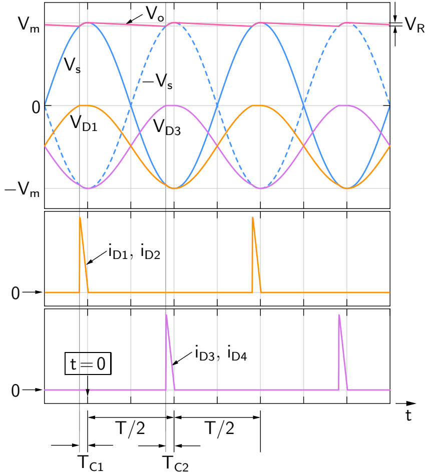
(a) filter capacitance:

Assuming $i_C = i_R = \dfrac{V_o}{R} \approx \dfrac{V_m}{R}$ in the discharge phase, we get

$$i_C = \frac{V_m}{R} = C\,\frac{\Delta V_o}{\Delta t} \approx C\,\frac{V_R}{T/2} \rightarrow V_R = V_m\,\frac{T}{2RC}.$$

Full-wave rectifier with capacitor filter





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$$\rightarrow C = \frac{1}{2}\,\frac{V_m}{V_R}\,\frac{T}{R} = \frac{1}{2}\,\frac{16\,\text{V}}{2\,\text{V}}\,\frac{20\,\text{ms}}{100\,\Omega} = 800\,\mu\text{F}.$$

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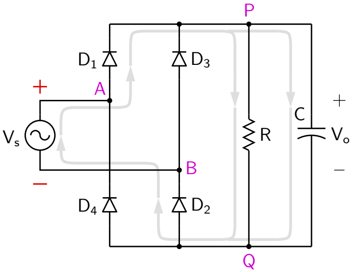
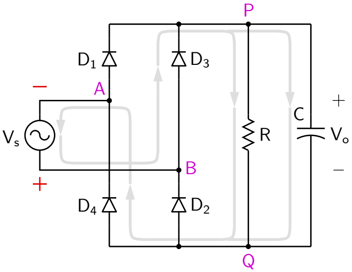
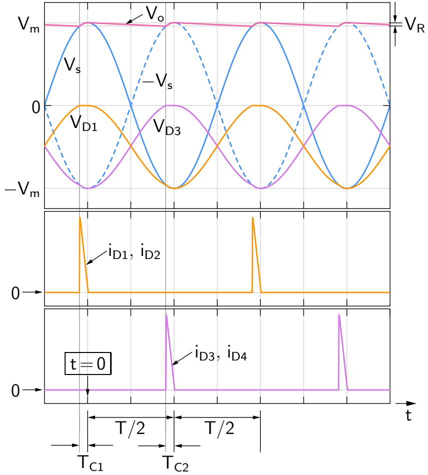
Full-wave rectifier with capacitor filter

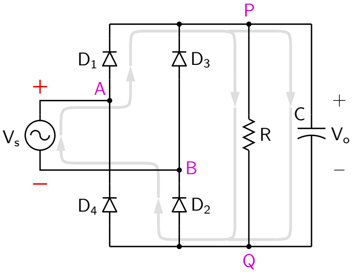


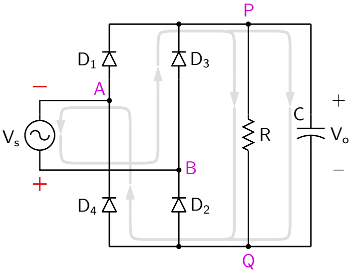


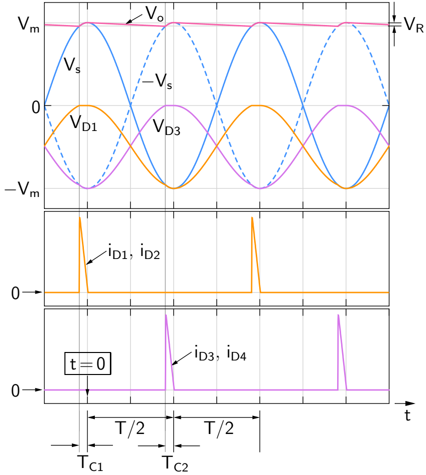


(b) Average diode current

Full-wave rectifier with capacitor filter



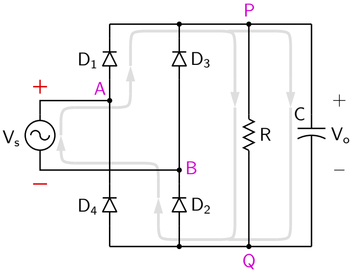


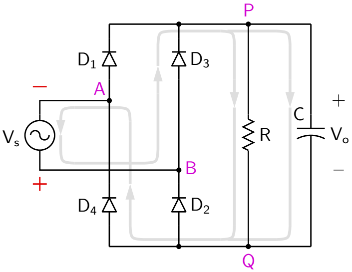


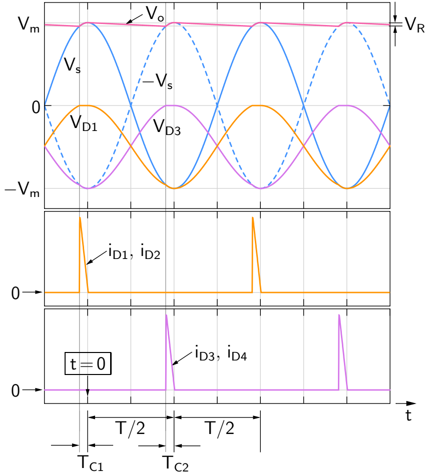
(b) Average diode current

Half of the charge lost by the capacitor is supplied by i_{D1} $(= i_{D2})$, and the other half by i_{D3} $(= i_{D4})$.

Full-wave rectifier with capacitor filter







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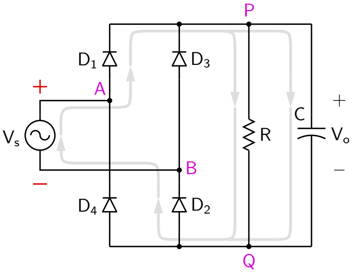
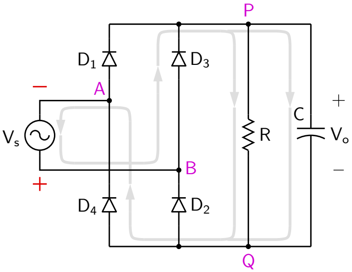
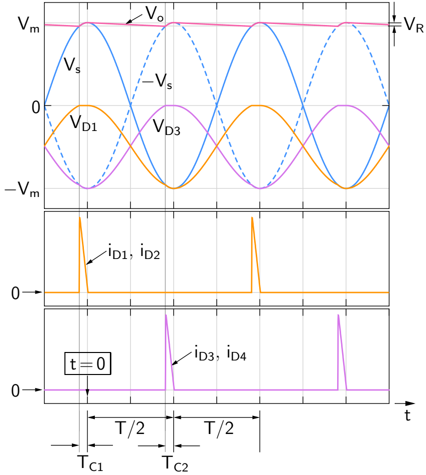
$$i_D^{av} = \frac{1}{T} \times \frac{1}{2} \times (\text{Charge lost in one cycle})$$







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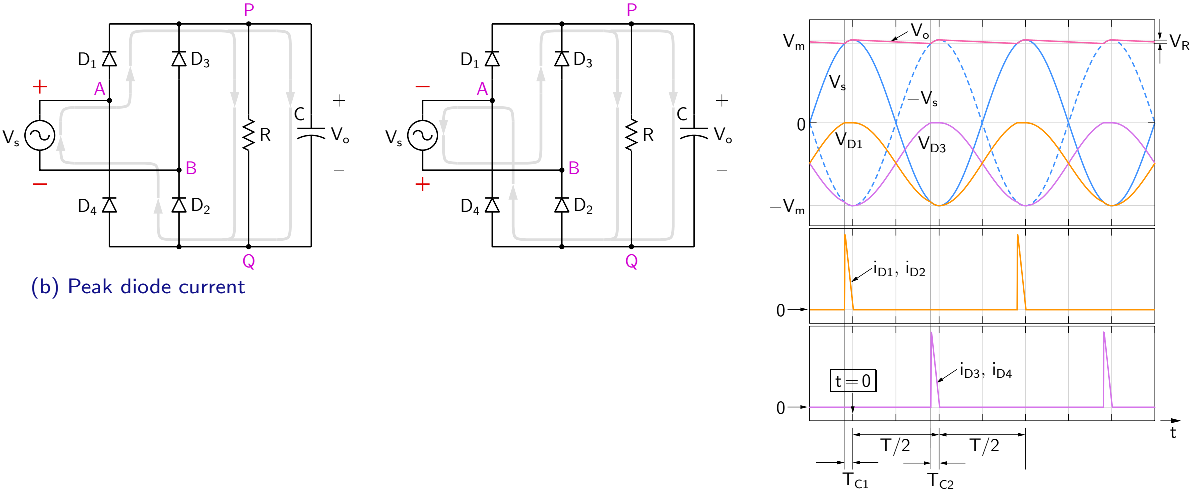
$$i_D^{av} = \frac{1}{T} \times \frac{1}{2} \times \text{(Charge lost in one cycle)}$$

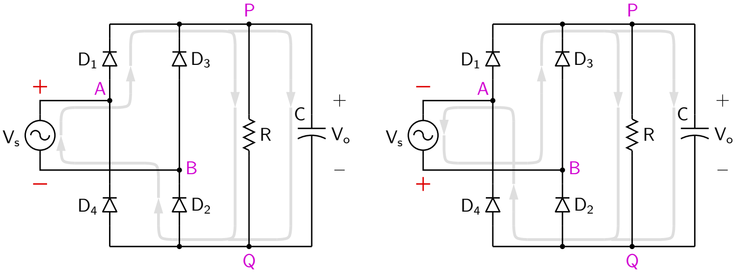
$$\approx \frac{1}{T} \times \frac{1}{2} \times \left(\frac{V_m}{R} \times T \right) = \frac{V_m}{2R} = \frac{16\,\text{V}}{2 \times 100\,\Omega} = 80\,\text{mA}.$$

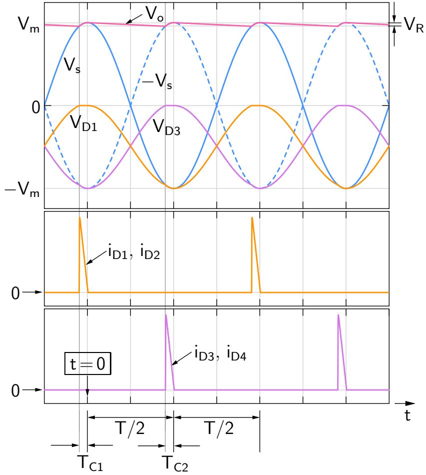
Full-wave rectifier with capacitor filter



(b) Peak diode current

Full-wave rectifier with capacitor filter



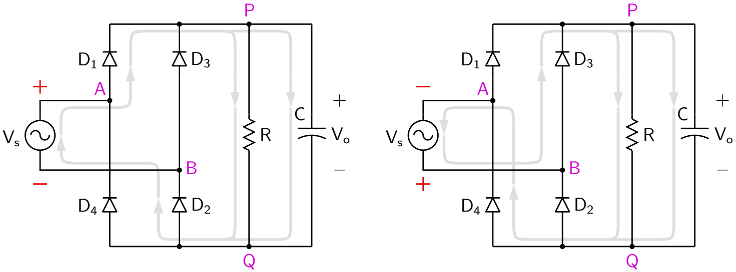


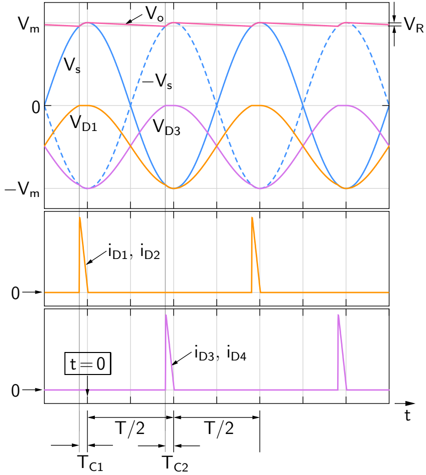
(b) Peak diode current

$$i_{D1}^{\text{peak}} = C\,\frac{d}{dt}\,(V_m \cos\omega t)\bigg|_{t=-T_{C1}} + \frac{V_m}{R}$$

$$= -\omega C\, V_m \sin(-\omega T_{C1}) + \frac{16\ \text{V}}{100\ \Omega}$$

$$= \omega C\, V_m \sin\omega T_{C1} + 0.16$$





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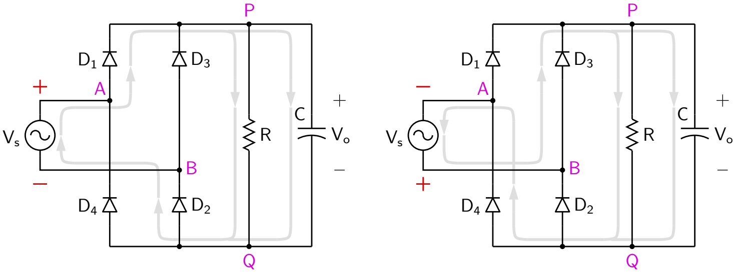
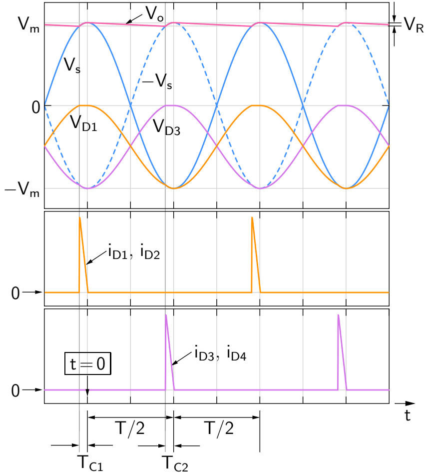
$$= -\omega C\, V_m \sin(-\omega T_{C1}) + \frac{16\,\text{V}}{100\,\Omega}$$

$$= \omega C\, V_m \sin\omega T_{C1} + 0.16$$

$$\omega T_{C1} = \cos^{-1}\left(1 - \frac{V_R}{V_m}\right) = \cos^{-1}\left(1 - \frac{2}{16}\right) = 29^\circ .$$

Full-wave rectifier with capacitor filter





(b) Peak diode current

$$i_{D1}^{peak} = C\,\frac{d}{dt}\,(V_m \cos\omega t)\Big|_{t=-T_{C1}} + \frac{V_m}{R}$$

$$= -\omega C\, V_m \sin(-\omega T_{C1}) + \frac{16\,\text{V}}{100\,\Omega}$$

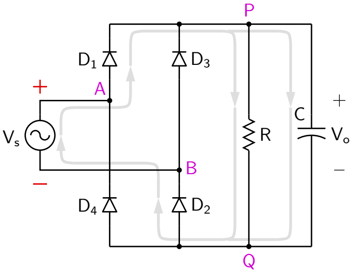
$$= \omega C\, V_m \sin\omega T_{C1} + 0.16$$

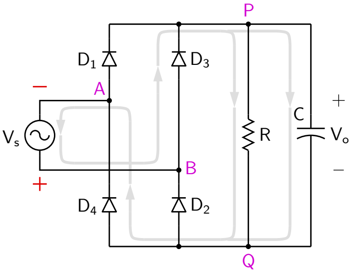
$$\omega T_{C1} = \cos^{-1}\left(1 - \frac{V_R}{V_m}\right) = \cos^{-1}\left(1 - \frac{2}{16}\right) = 29^\circ.$$

$$i_{D1}^{peak} = 2\pi \times 50 \times 800 \times 10^{-6} \times 16 \times \sin 29^\circ + 0.16$$

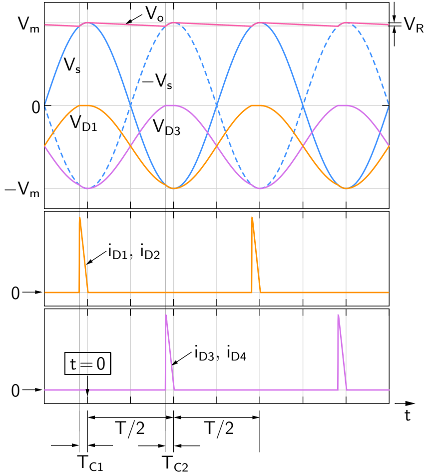
$$= 1.95 + 0.16 = 2.1\,\text{A}.$$

Full-wave rectifier with capacitor filter

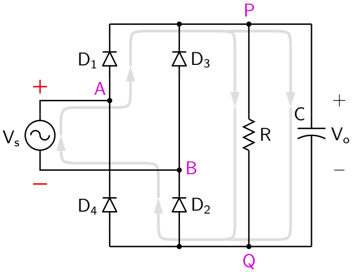


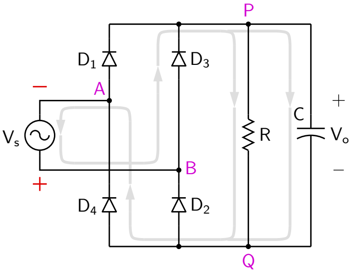


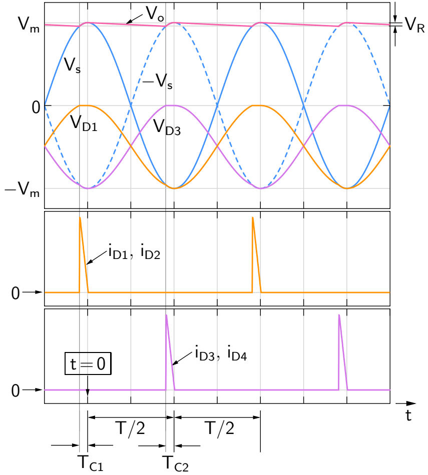
(c) Maximum reverse bias $= \ V_m = 16\,\mathrm{V}$.



Full-wave rectifier with capacitor filter







(c) Maximum reverse bias $=\ V_m = 16\,\mathrm{V}$.

SEQUEL file: `diode_rectifier_4.sqproj`

Comparison of half-wave and full-wave (bridge) rectifiers with capacitive filter

For the same source voltage ($V_m \sin \omega t$), load (R), and ripple voltage (V_R), compare the half-wave and full-wave rectifiers.

Comparison of half-wave and full-wave (bridge) rectifiers with capacitive filter

For the same source voltage ($V_m \sin \omega t$), load (R), and ripple voltage (V_R), compare the half-wave and full-wave rectifiers.

Parameter	Half-wave	Full-wave
Number of diodes	1	4
Filter capacitance	C	$C/2$
Average diode current	i_D^{av}	$i_D^{\text{av}}/2$
Peak diode current	i_D^{peak}	$i_D^{\text{peak}}/2$
Maximum reverse voltage	$2\,V_m$	V_m