Circuit Theory and Electronics Fundamentals

Lecture 14: Diode circuits

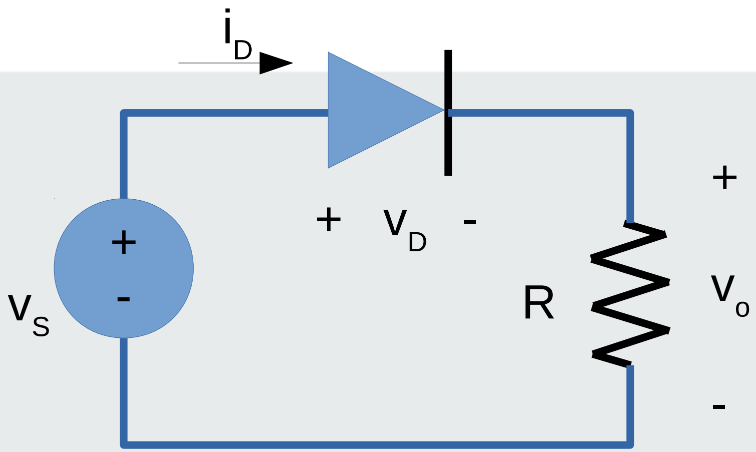
- ***<u>AC/DC converter</u>***
  - Half-wave rectifier circuit revisited
  - Full-wave rectifier circuit
  - Limiter circuit
  - Envelope detector circuit
  - Voltage regulator circuit

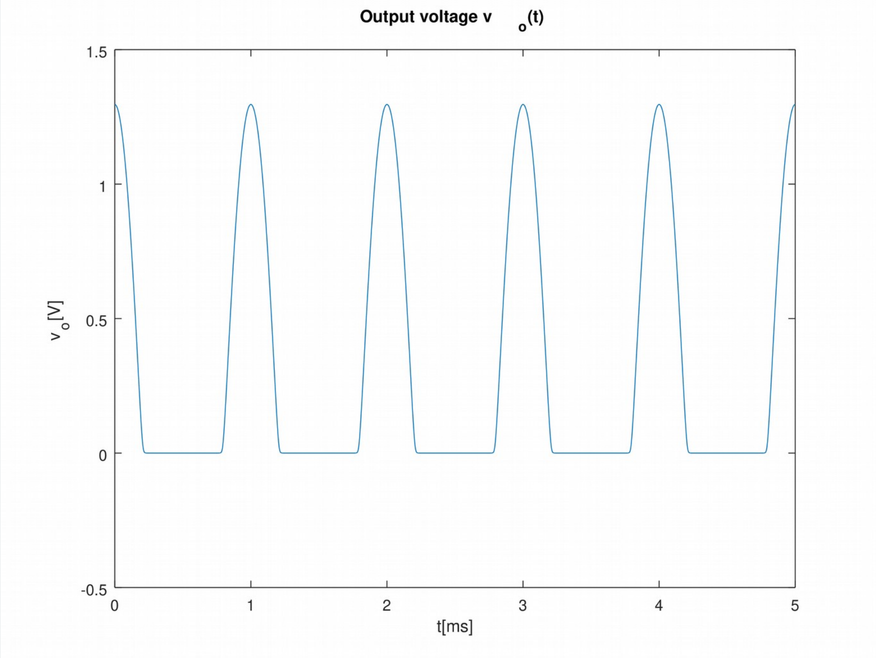
Half-wave rectifier revisited

$$v_s(t) = A\cos(\omega t)$$

$$v_O = \begin{cases} v_s - v_D, & D_{ON} \\ 0, & D_{OFF} \end{cases}$$

$$i_D = \begin{cases} \frac{v_O}{R}, & D_{ON} \\ 0, & D_{OFF} \end{cases}$$



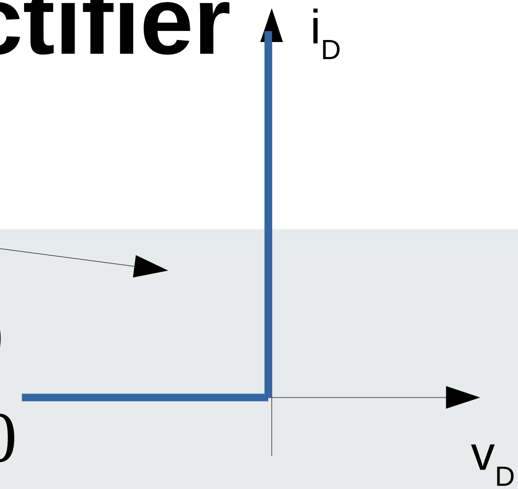


Octave script l11.m solves 1 non-linear equation for v, for each time instant t

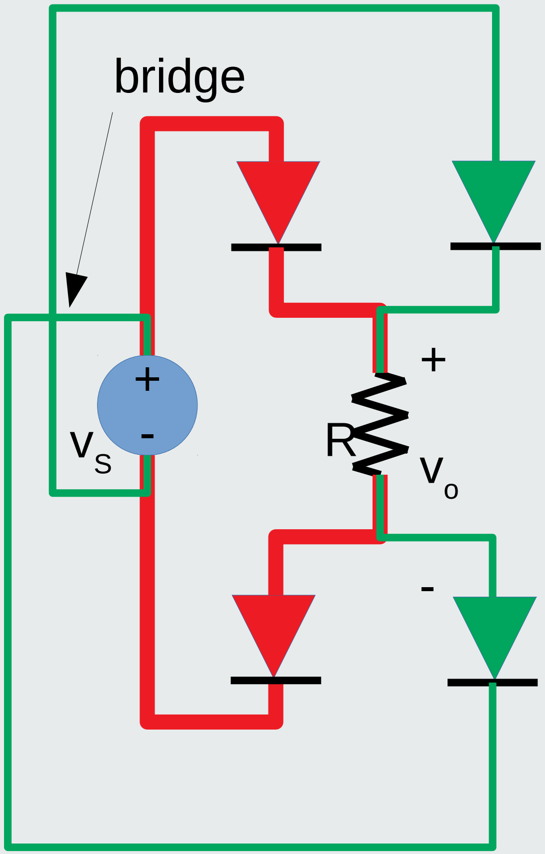
HALF WAVE RECTIFIER CIRCUIT

Full-wave bridge rectifier circuit

Assume ideal diodes



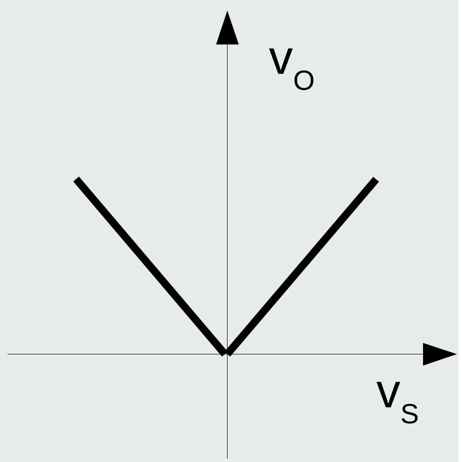
$$i_D = \begin{cases} 0, & v_D < 0 \\ positive, & v_D = 0 \end{cases}$$

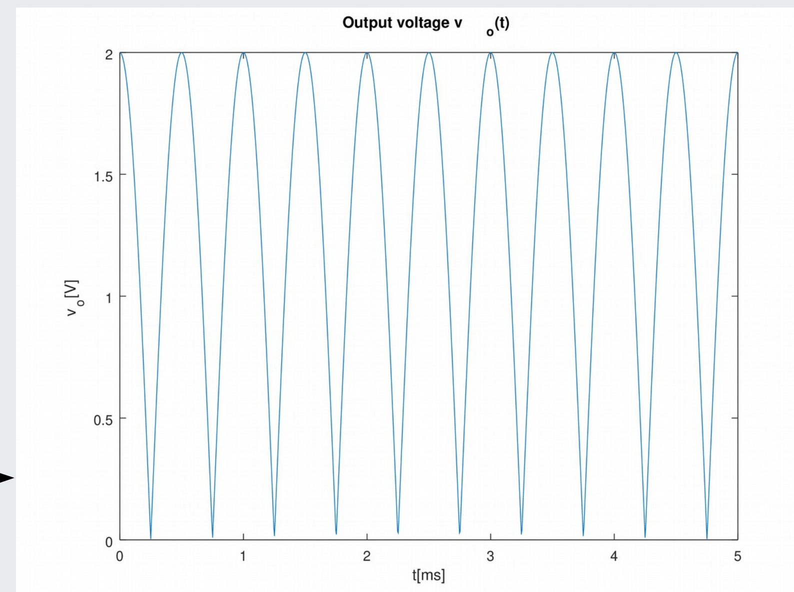


$$v_O = \begin{cases} v_S, & v_S \geq 0 \\ -v_S, & v_S < 0 \end{cases}$$

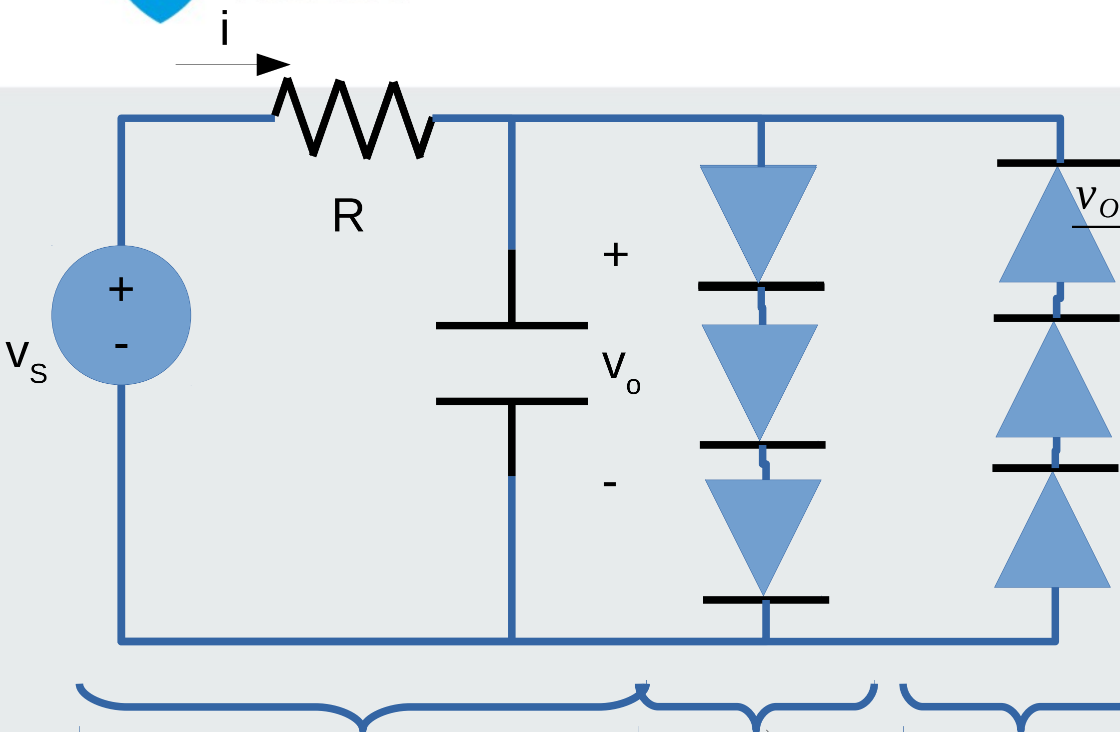
$$\boxed{v_O = |v_S|}$$

Full-wave rectifier computes absolute value





Limiter circuit



KCL:

$$\frac{v_O - v_S}{R} + C\frac{dv_O}{dt} + I_S\left(e^{\frac{v_O}{3\eta V_T}} - 1\right) + I_S\left(e^{\frac{-v_O}{3\eta V_T}}\right) = 0$$

Non-linear differential equation!!

Out of the scope of this course.

Using (V_{ON}) diode model

$$v_O(t) = \begin{cases} -3V_{ON}, & V_{LPF} \le -3V_{ON} \\ v_{LPF}(t), & -3V_{ON} \le V_{LPF} \le 3V_{ON} \\ 3V_{ON}, & V_{LPF} \ge 3V_{ON} \end{cases}$$

1st order low pass filter

Using the forced solution only:

$$\tilde{V}_{LPF} = \frac{1}{1 + j\omega RC}\tilde{V}_S$$

$$v_{LPF}(t) = \left|\frac{\tilde{V}_S}{1 + j\omega RC}\right| \cos(\omega t - \arctan(\omega RC))$$

Positive voltage limiter

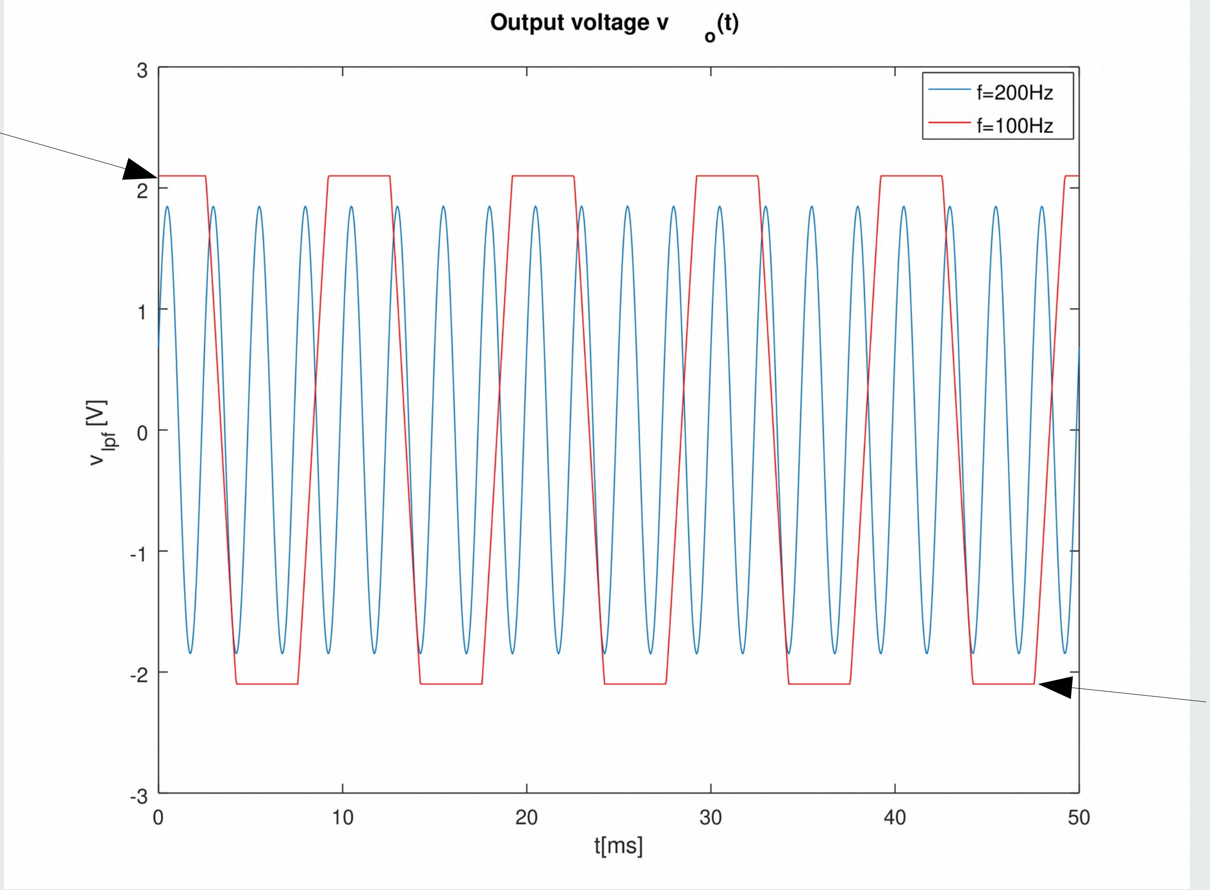
$$v_O(t) \le 3V_{ON}$$

Negative voltage limiter

$$v_O(t) \ge -3V_{ON}$$

Limiter circuit approximate analytical solution

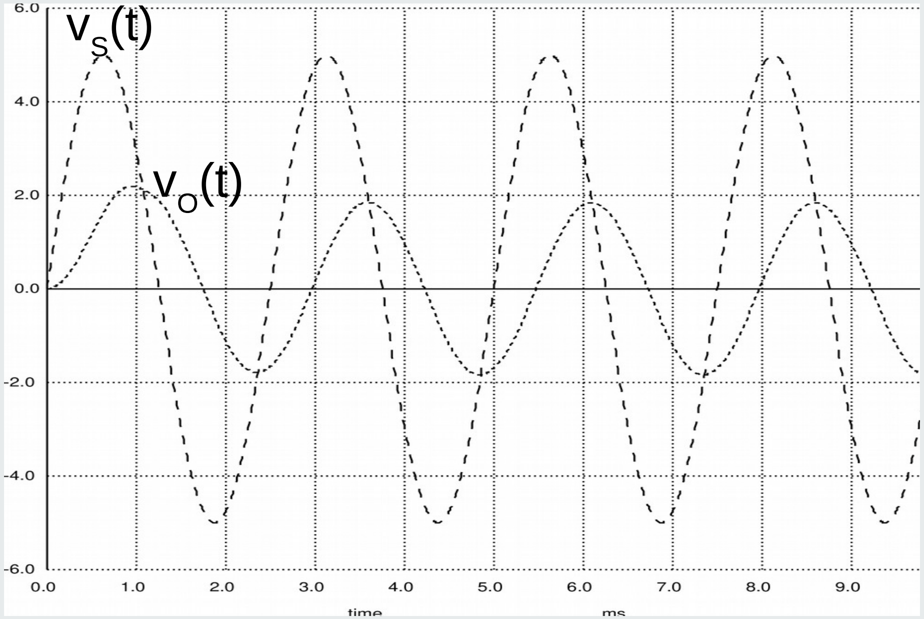
Positive limit



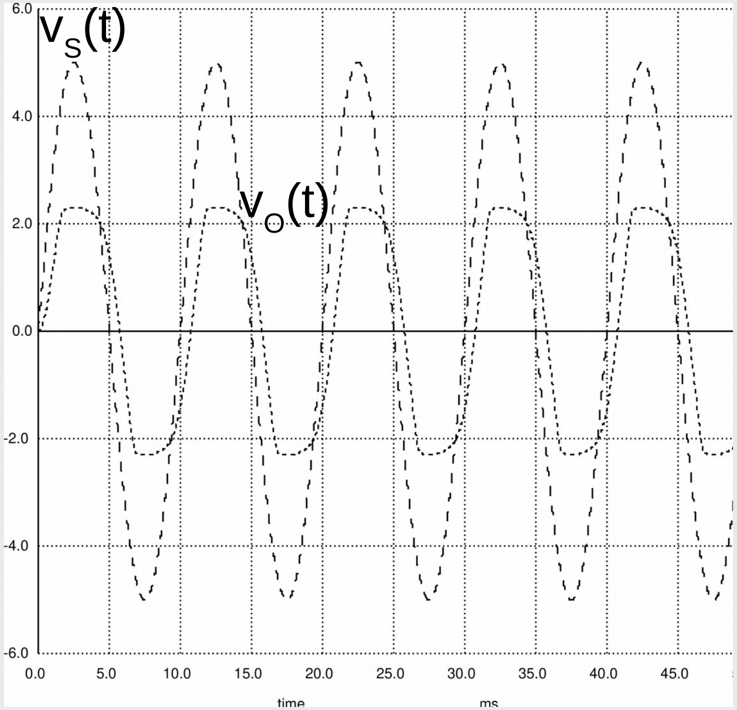
Negative limit

Approximate Octave solution using (V_{ON}) diode model (see l14.m)

Limiter circuit simulation solution



f=400Hz



f=100Hz

Ngspice solution using the default diode model (see l14.net)

Ngspice's Diode Model

SPICE Diode Model Parameters

	name	parameter	units	default	example	area
1	IS	saturation current	A	1.0e-14	1.0e-14	*
2	RS	ohmic resistanc	Ohm	0	10	*
3	N	emission coefficient	-	1	1.0	
4	TT	transit-time	sec	0	0.1ns	
5	CJO	zero-bias junction capacitance	F	0	2pF	*
6	VJ	junction potential	V	1	0.6	
7	M	grading coefficient	-	0.5	0.5	
8	EG	band-gap energy	eV	1.11	1.11 Si	
9	XTI	saturation-current temp.exp	-	3.0	3.0 pn 2.0 Schottky	
10	KF	flicker noise coefficient	-	0		
11	AF	flicker noise exponent	-	1		
12	FC	coefficient for forward-bias depletion capacitance formula	-	0.5		
13	BV	reverse breakdown voltage	V	infinite	40.0	
14	IBV	current at breakdown voltage	V	1.0e-3		
15	TNOM	parameter measurement temperature	deg C	27	50	

Ngspice uses a complex 15-parameter diode model

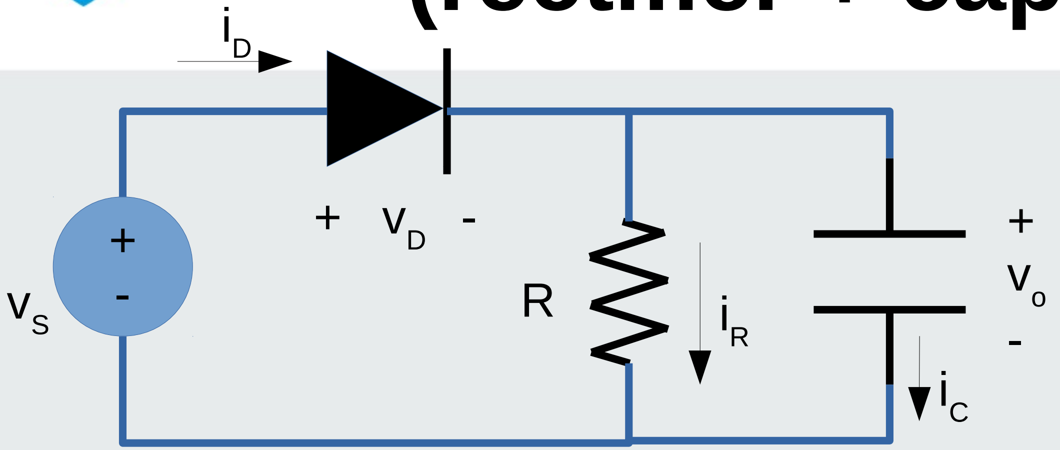
In this course we use the Default parameters

Users can override these parameters. For example:

.MODEL Dmine D (IS=76.9n)

Creates model Dmine and overrides parameter IS

Envelope detector circuit (rectifier + capacitor)



Using ideal diode model

At t=0 D is ON

$$v_O(t)=v_S(t)$$

$$v_s(t)=A\cos(\omega t)$$

$$i_R=\frac{v_S}{R}$$

$$v_O=\begin{cases} v_s, & D_{ON} \\ -R\,i_C, & D_{OFF} \end{cases}$$

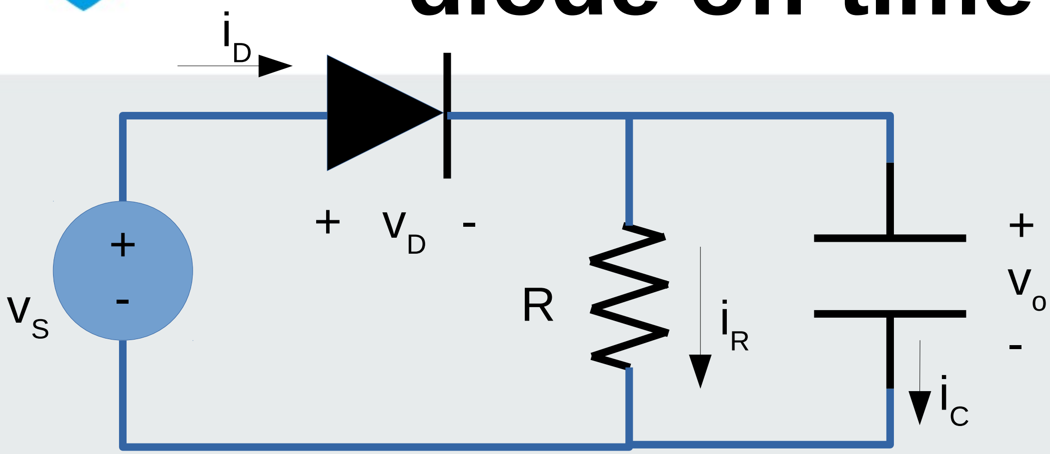
$$i_C=C\frac{dv_S}{dt}=-C\,A\,\omega\sin(\omega t)$$

$$i_C=C\frac{dv_o}{dt}$$

$$i_D=i_R+i_C \qquad \text{(KCL)}$$

i_C is negative and growing more negative with the time derivative of $v_O = v_S - V_{ON}$ ...

Envelope detector circuit: diode off time instant



$$i_D = i_R + i_C$$

At t=t_{OFF} D goes OFF

Compute t_{OFF} using ideal diode model:

$$i_R = -i_C$$

$$\frac{v_S}{R} = -C\frac{dv_S}{dt}$$

$$\frac{A}{R}\cos(\omega t_{OFF}) = C\,A\,\omega\sin(\omega t_{OFF})$$

$$t_{OFF} = \frac{1}{\omega}\,atan\left(\frac{1}{\omega RC}\right)$$

$$t \geq t_{OFF} \Rightarrow$$

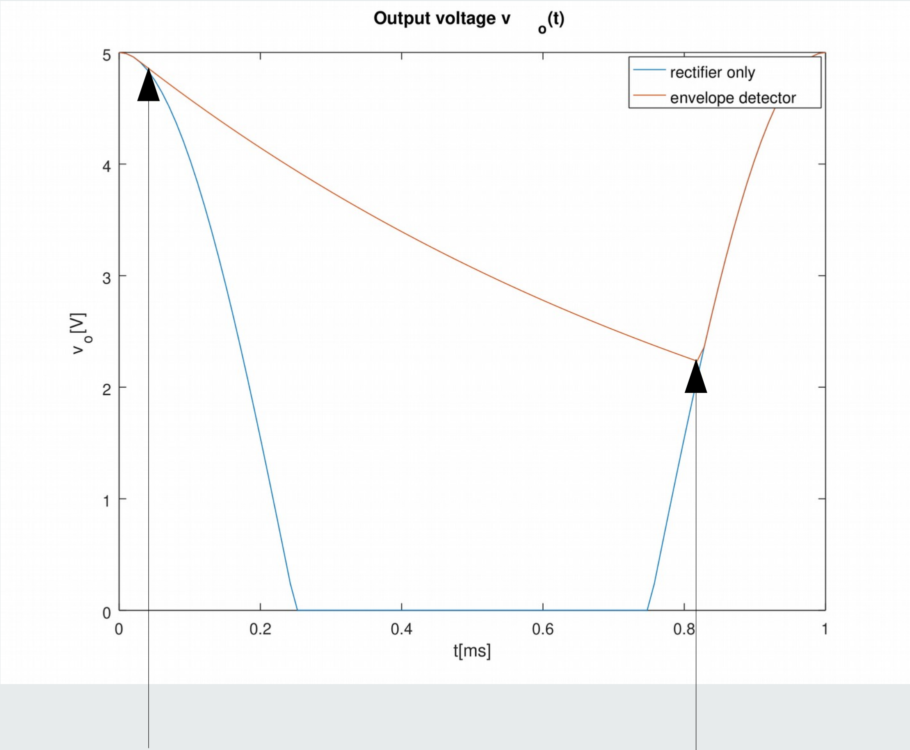
$$v_O(t) = A\cos(\omega t_{OFF})\,e^{-\frac{t-t_{OFF}}{RC}}$$

i_C is negative and growing more negative with the time derivative of v_O…

When i_R=-i_C, the diode current i_D becomes null
The diode goes OFF and $v_S < v_O$

C discharges through R

Envelope detector plot



t_{OFF}

t_{ON}

Diode goes OFF

Diode goes ON

At t=t_{ON} D goes ON

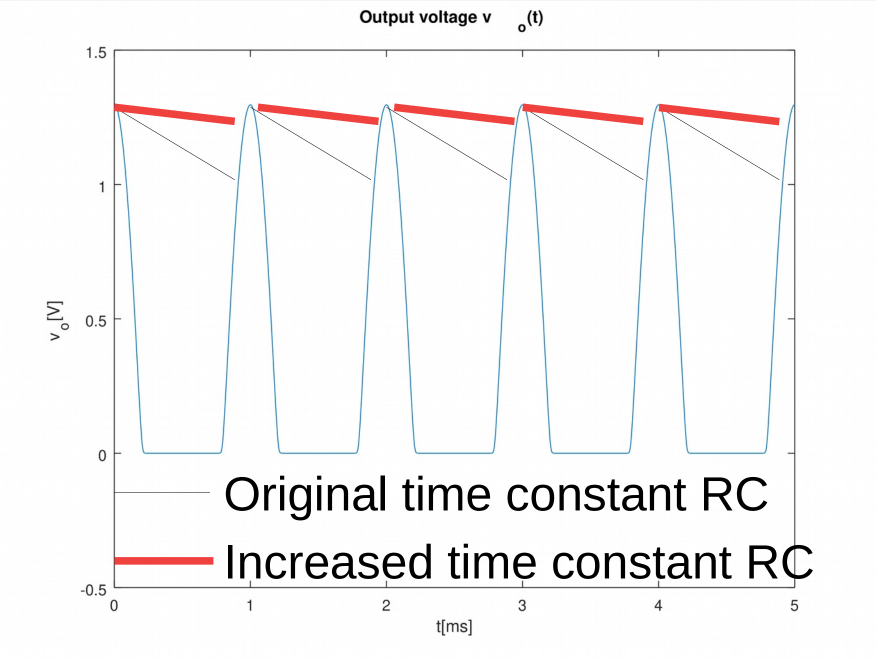
Compute t_{ON} using ideal diode model:

$$v_S(t_{ON}) = A\cos(\omega t_{OFF})\, e^{-\frac{t_{ON}-t_{OFF}}{RC}}$$

$$A\cos(\omega t_{ON}) = A\cos(\omega t_{OFF})\, e^{-\frac{t_{ON}-t_{OFF}}{RC}}$$

t_{ON} is given by solving the above non-linear equation approximately using Octave

Voltage ripple problem



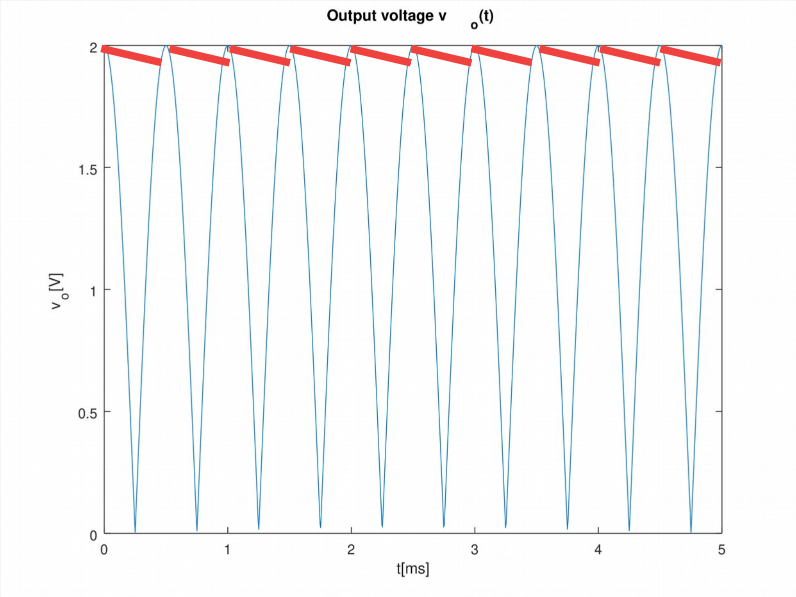
Approximate voltage ripple with half-wave rectifier circuit:

$$V_{ripple} = v_O(0) - v_O(T) = A\left(1 - e^{-\frac{T}{RC}}\right)$$

- Problem: v_O still shows oscillations at frequency f!
- A rippling power supply may affect application
  - Examples: audio or video applications
- AC/DC conversion imperfect
- Solution 1: increase time constant
  - Increase C, R or both
  - Disadvantage: larger C and R is expensive, especially in integrated circuits
- For small ripple:

  $t_{OFF} \approx 0$ and $t_{ON} \approx T$

Improving voltage ripple with full-wave rectifier circuit

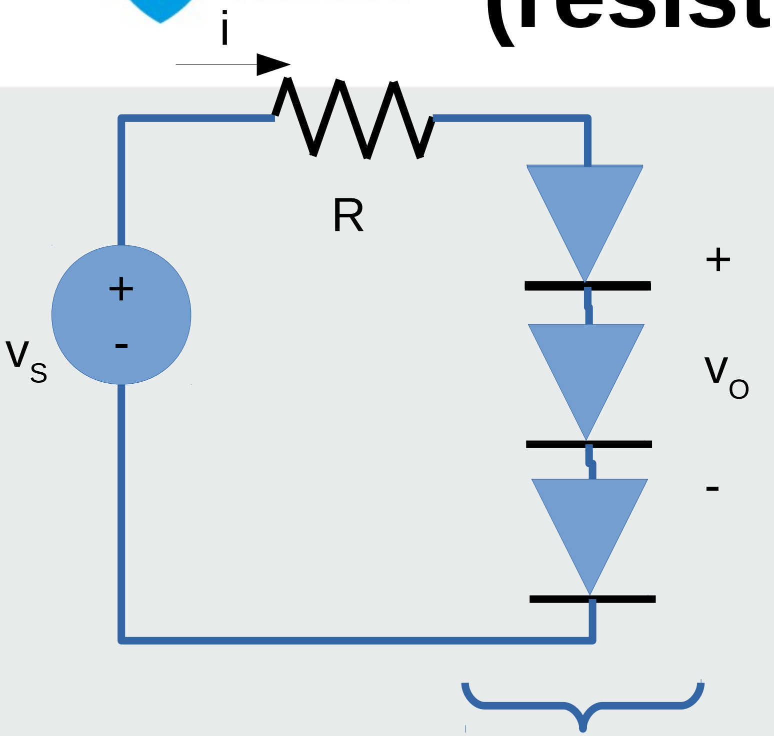


Approximate voltage ripple with full-wave rectifier circuit:

$$V_{ripple} = v_O(0) - v_O\left(\frac{T}{2}\right) = A\left(1 - e^{-\frac{T}{2RC}}\right)$$

- Solution 2: Use a full-wave rectifier
- v_O oscillates at frequency 2f with less amplitude
- Doubling the frequency and halving the amplitude may solve the problem in some applications
- Cheap solution for integrated circuits
  - Diodes and transistors can be very small and thus inexpensive

Voltage regulator circuit (resistor + limiter)



- The voltage regulator attenuates oscillations in the input signal without frequency dependence (unlike filters)
- Takes advantage of the non-linear diode characteristic

Positive voltage limiter

$$v_O(t) \leq 3V_{ON}$$

Separate DC and incremental components:

$$v_S = V_S + v_s, \quad V_S > 3V_{ON}$$

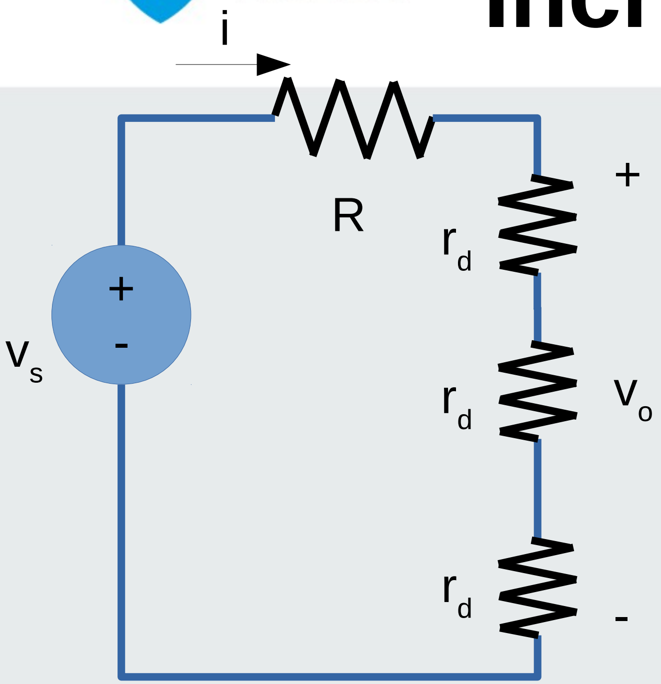
Ensures forward bias

$$v_O = V_O + v_o$$

$$V_O = 3V_{ON}$$

Show that: $\Delta v_O \ll \Delta v_S$

Voltage regulator circuit – Incremental analysis



$$v_o = \frac{3r_d}{3r_d + R} v_s$$

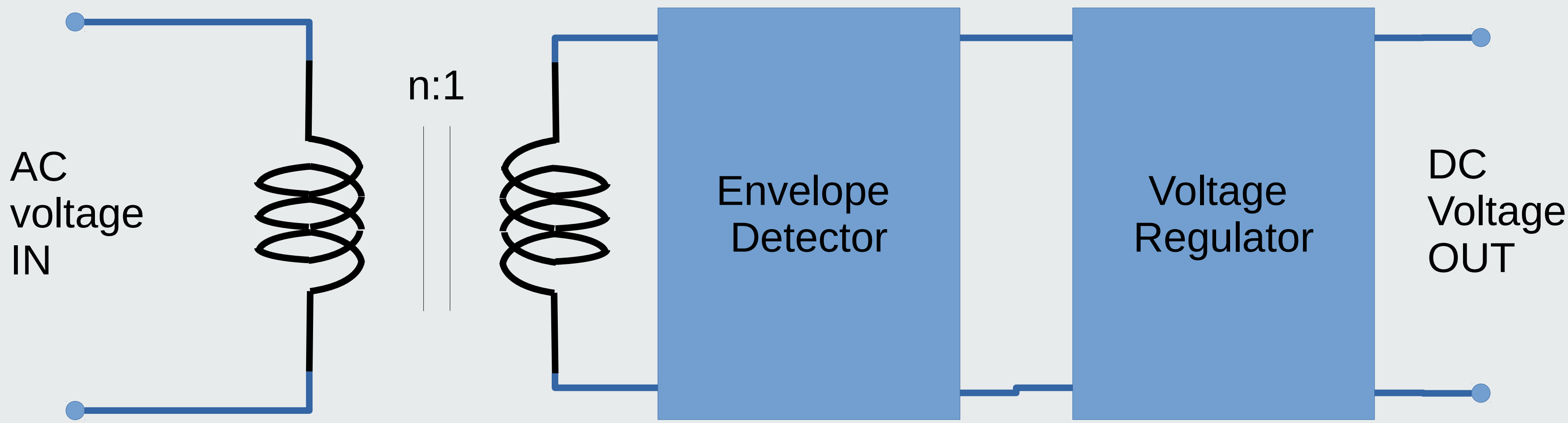
Voltage Divider!

$$3r_d \ll R \Rightarrow v_o \approx 0$$

- Problem solved!
- Choose R much greater than diode incremental resistance

$$r_d = \frac{\eta V_T}{I_S e^{\frac{V_D}{\eta V_T}}}$$

AC/DC CONVERTER



- You can now build an AC/DC converter
- That's what lab assignment 3 is about
- Questions welcome!

Conclusion

- ***<u>AC/DC converter</u>***
  - Half-wave rectifier circuit revisited
  - Full-wave rectifier circuit
  - Limiter circuit
  - Envelope detector circuit
  - Voltage regulator circuit