AC to DC Converters

Objective:

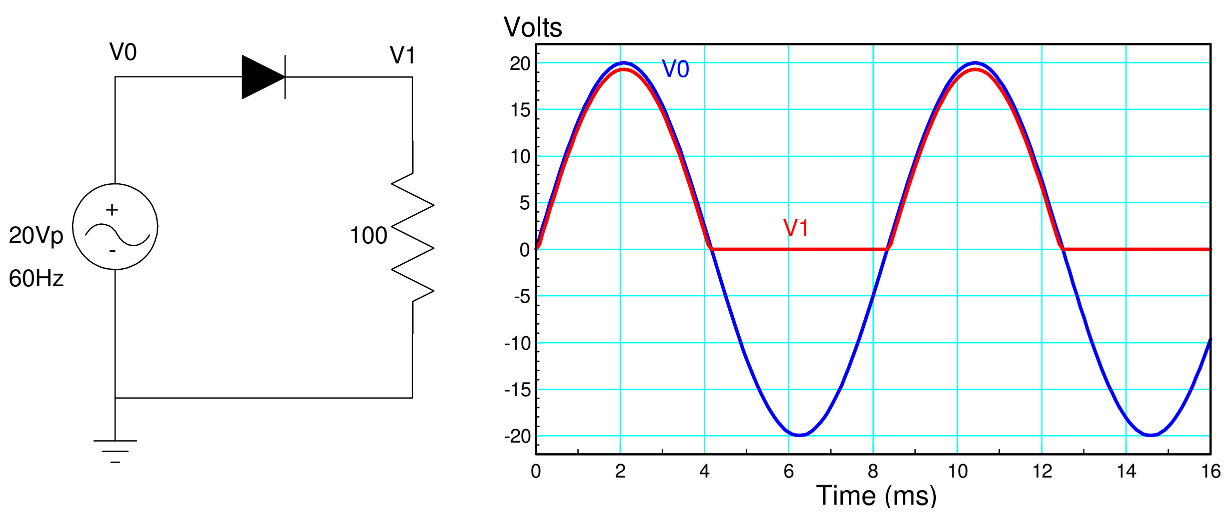
- Convert 60Hz AC to a DC signal.
- AC travels more efficiently over power grids than DC (transformers don't work at DC).
- DC works better for microcontrollers. (They don't like being turned on and off 60 times a second.)

Half-Wave and Full-Wave Rectifiers:

The heart of an AC to DC converter is the half-wave and full-wave rectifiers.

Diodes only allow current to flow one way. If you place a diode in series with an AC source as shown below, in effect the AC source behaves as a 1/2 wave rectified sine wave. The features of a 1/2 wave rectifier are

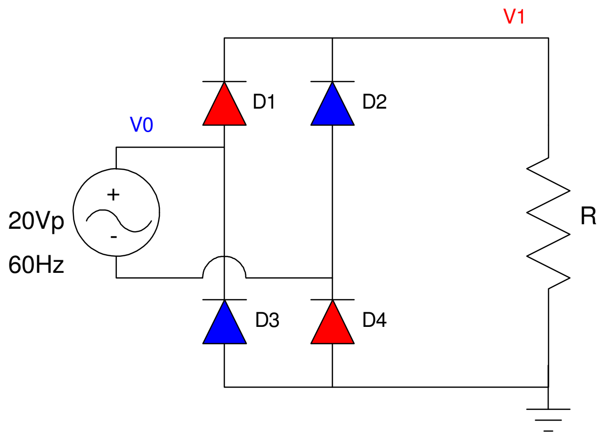
- It's simple: it only uses a single diode,
- You only lose 0.7V through the diode,
- The source (V0) and the load can share a common ground, and
- The frequency of the ripple at V1 is 60Hz

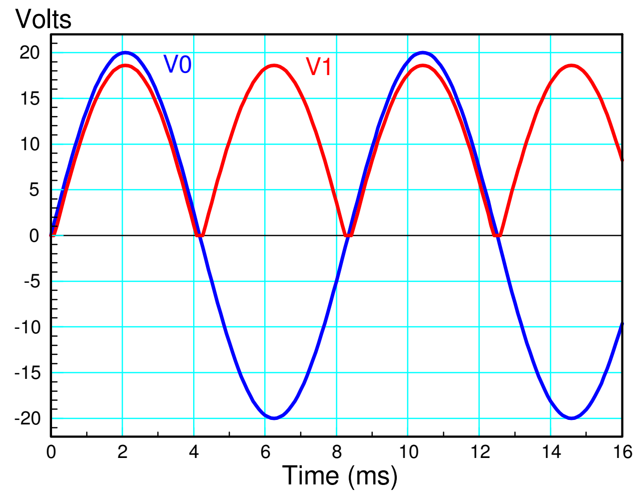


Half-wave rectifier. The diode only passes V0 when V0 > 0

A full-wave rectifier uses four diodes. The features of a full-wave rectifier are:

- It's a little more complex using four diodes
- You lose 1.4V from the source: any path passes through two diodes,
- The source and load cannot share a common ground (If you ground both the source (V0) and the load, diode D3 never turns on and you wind up with an expensive 1/2 wave rectifier), and
- The frequency of the ripple is 120Hz (twice the input frequency)



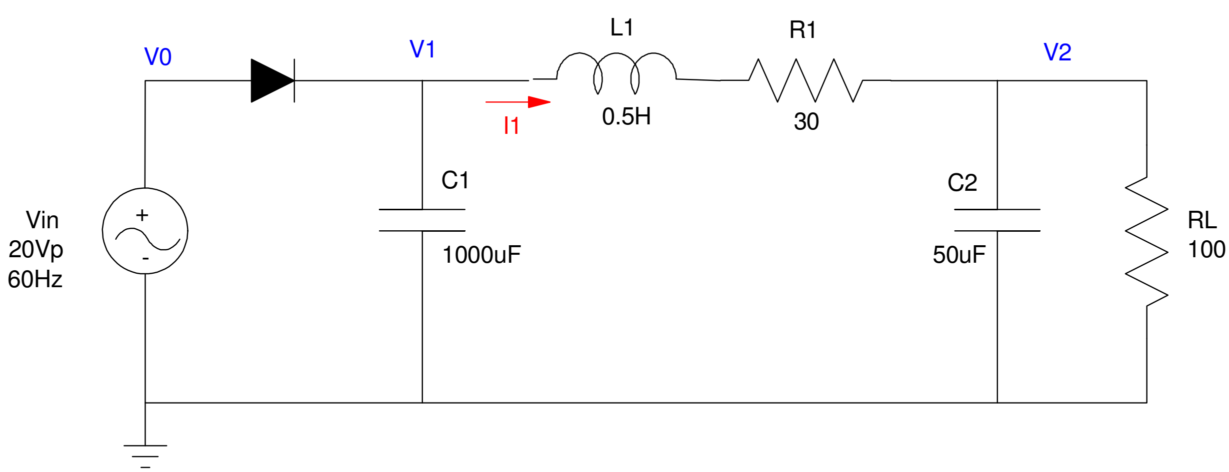


Full-wave rectifier. Diodes D1 and D4 turn on when V0 > 0. Diodes D2 and D3 turn on when V0 < 0.

AC to DC Converters: Analysis

The following circuit is a typical AC to DC converter:

- The diode acts as a 1/2 wave rectifier, passing only the positive portion of Vin.
- C1 acts as a battery: it stores energy and charges up to the peak of Vin (19.3V) and the powers the rest of the circuit when the diode turns off.
- L1 and R1 act as a filter. Their impedance at DC is low, passing the DC signal, while their impedance at 60Hz is high, blocking the AC signal and reducing the ripple at V2.
- C2 also acts as a filter. It's impedance at DC is high, having no affect on V2. At 60Hz, it's impedance is low, also reducing the ripple at V2.



Typical AC to DC converter. L1 and C2 are optional: they reduce the ripple at V2.

The procedure to analyze such a circuit is as follows:

Step 1: DC Analysis. This is actually a difficult circuit to analyze due to the nonlinear element (the diode). Several approximations allow you to get an answer which is close.

First, C1 will charge up to the peak of Vin, minus 0.7V due to the diode

max(V1) = 19.3V

Assume for now that V1 is fixed at 19.3V. The current, I1, will be

$$I_1 = \frac{19.3V}{30\Omega+100\Omega} = 148.5mA$$

(capacitors and inductors have no affect at DC).

Step 2: AC Analysis for V1. The ripple at V1 comes from the equation for capacitors

$$I = C\frac{dV}{dt}$$

Plugging in numbers

$$148.5mA = 1000\mu F\,\frac{dV}{1/60s}$$

$$dV = 2.4744Vpp$$

The voltage at V1 will have a DC and AC component

DC: $V_1 = 19.3V - \frac{1}{2}(2.4744V_{pp})$

$$V_1 = 18.06V$$

AC: $V_1 = 2.4744V_{pp}$

Step 3: DC Analysis for V2. By voltage division

$$V_2 = \left(\frac{R_L}{R_L+R_1}\right)V_1 = \left(\frac{100}{100+30}\right)18.06V$$

$$V_2 = 13.8945V$$

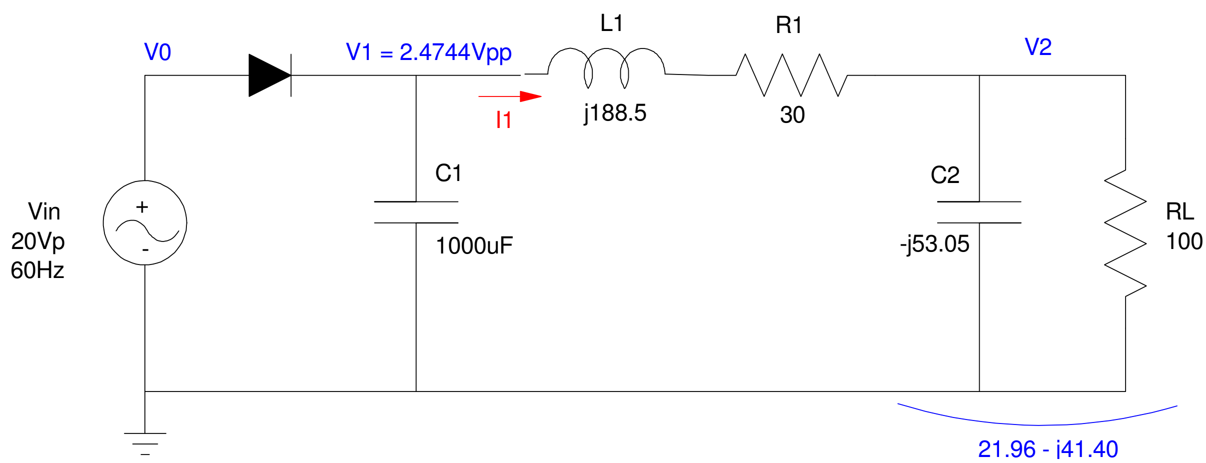
Step 4: AC analysis for V2. Using phasor analysis

$$V_1 = 2.4744 + j0$$

$$\omega = 377\ \frac{rad}{\sec}$$

$$L \to j\omega L = j188.5\Omega$$

$$C_2 \to \frac{1}{j\omega C} = -j53.05\Omega$$



Combine RL and C2 in parallel

$$Z_2 = \left(\frac{1}{100} + \frac{1}{-j53.05}\right)^{-1} = 21.96 - j41.40$$

By voltage division

$$V_2 = \left(\frac{Z_2}{Z_2+Z_1}\right) V_1$$

$$V_2 = \left(\frac{21.96-j41.40}{(21.96-j41.40)+(30+j188.5)}\right)(2.4744 V_{pp})$$

$$V_2 = -0.5031 - j0.5472$$

All we care about is the magnitude (the phase tells you that V2 is delayed in time from V1, which we don't care)

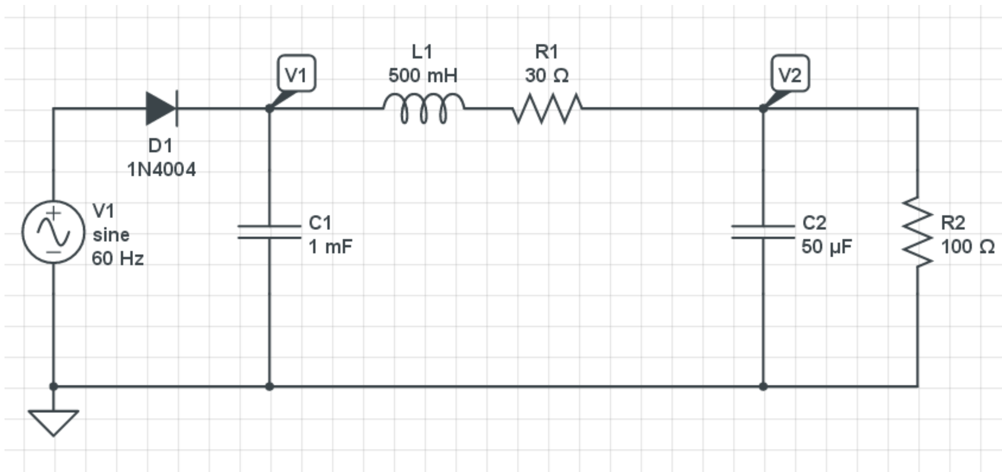
$$|V_2| = 0.7433 V_{pp}$$

So, V2 should be 13.8945V (DC) with a ripple of 0.7433Vpp

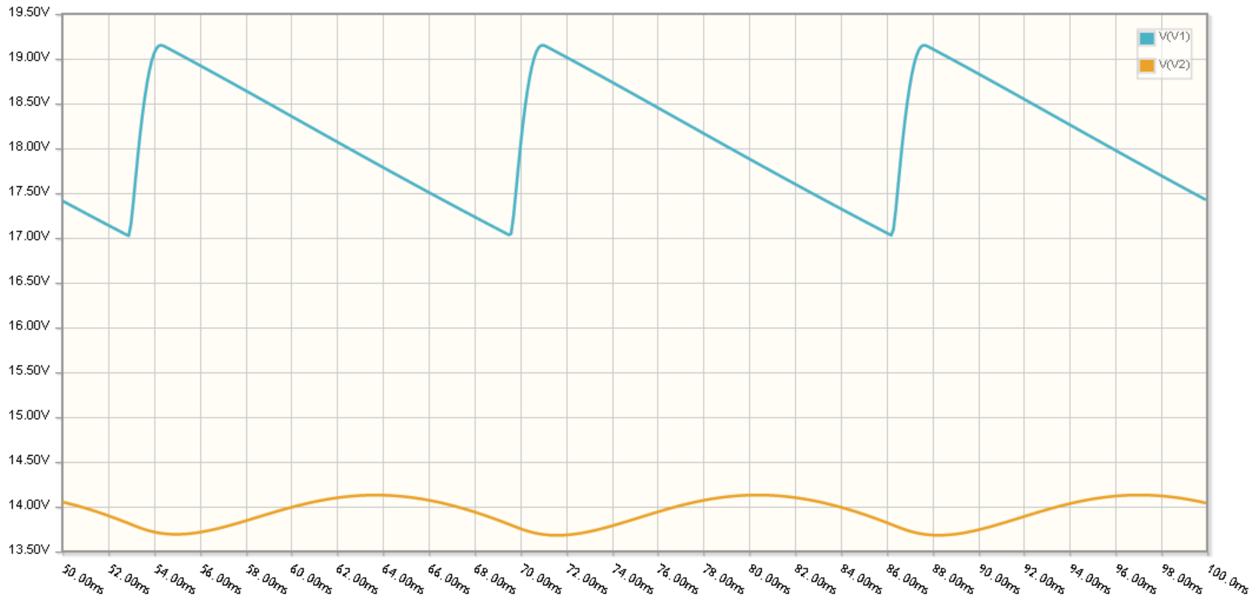
Checking in CircuitLab, the results are

	V1		V2	
	DC	AC	DC	AC
Calculation	18.08V	2.4744 Vpp	13.8945V	0.7433 Vpp
CircuitLab	18.08V	2.110 Vpp	13.90 V	0.450 Vpp

Note that our calculations are a little bit conservative. This is due to making several approximations in order to solve for V2.



CircuitLab circuit for an AC to DC converter



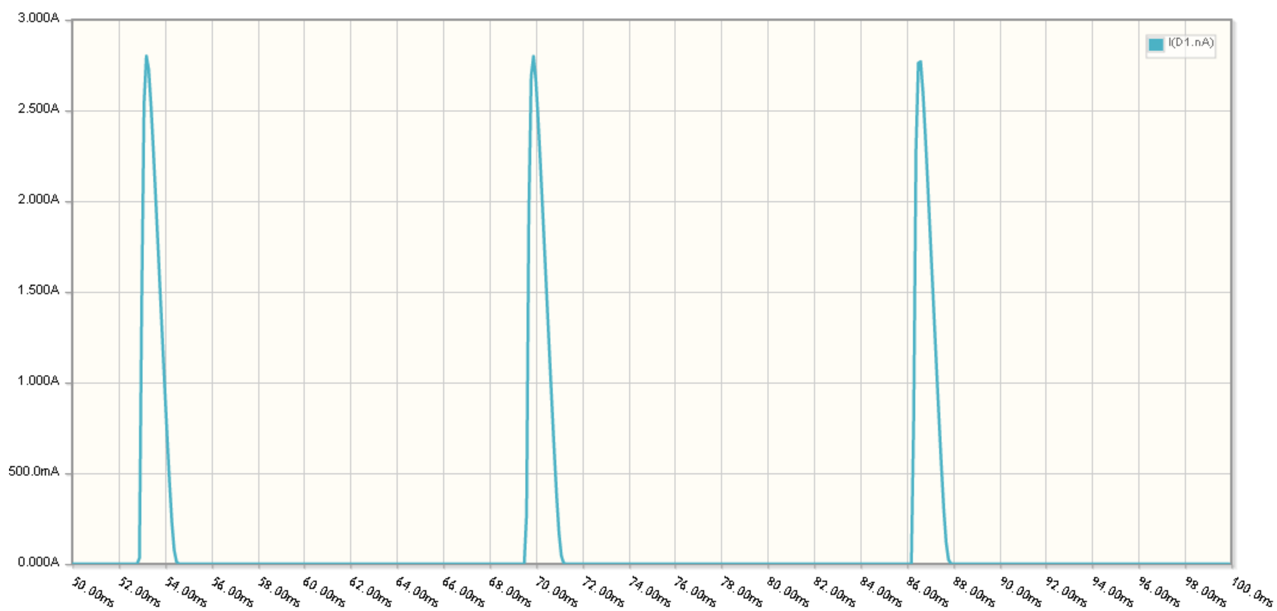
Transient simulation for the AC to DC converter

One problem with AC to DC converters of this sort is the current from the source has spikes:

- When Vin reaches 20V, the diode turns on, charging up the capacitor to 19.3V.
- The energy (i.e. current) has to be enough to keep the circuit powered for the time the diode turns off.
- In this case, that means the peak current is almost 3A even though we're just delivering 148mA to the load.

These current spikes mean...

- Your AC power supply needs to be able to deliver up to 3A peak.
- If this AC power is produced using a transformer, the spikes create high-frequency currents in the transformer. These increase the eddy current and hysteresis losses in the transformer.
- If you have a lot of AC to DC converters on a power grid, the 3-phase currents will no longer cancel when added together. This can result in burning out the neutral lines.



The AC to DC converter produces current spikes from the source. This can cause problems for a power grid.

Ideally, what we want is

- The current from the source is a nice clean 60Hz sine wave, while
- The current to the load is a nice clean DC signal, with
- 90% or higher efficiency.

One way to do this is to use an AC motor to drive a DC generator. We're not about to use a motor generator combination for every LED light bulb, however.

What we need is a way to do this with electronics. So far, no-one has designed a circuit to do that. Whoever comes up with this design will be worth billions.

AC to DC Converters: Design.

Design an AC to DC converter to meet the following requirements:

Input: 60Hz, 20Vp sine wave capable of 500mA (i.e. a wall transformer)

Output:

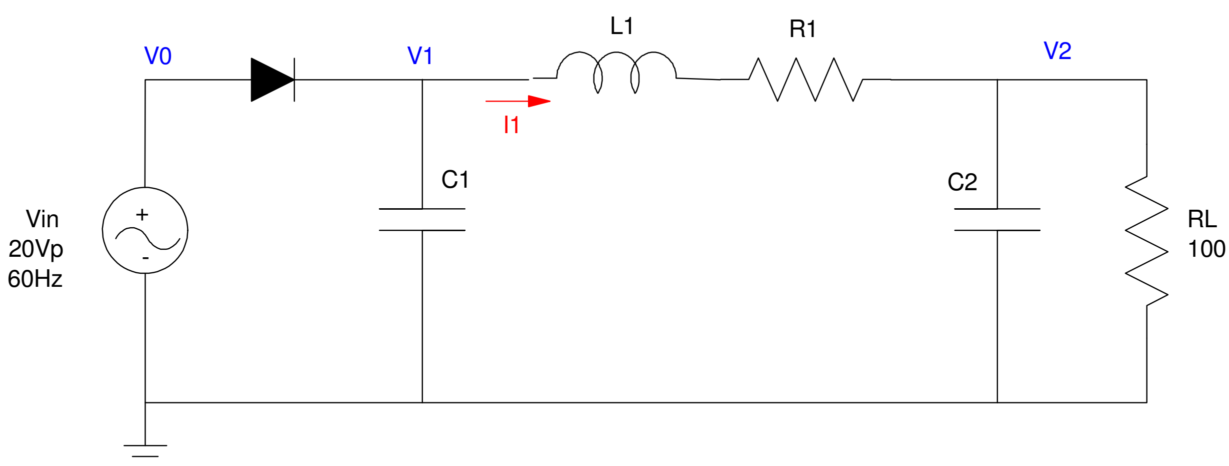
- 100 Ohm resistor
- V1 = 1Vpp
- V2 = 100mVpp

The procedure to design an AC to DC converter is as follows.

Step 1: Pick your favorite rectifier: half wave of full wave.

- Full-wave requires smaller L1 and C2 since the frequency at V1 is 120Hz
- Half-wave can use a common ground for everything (V1 = 60Hz).

Assume a half-wave rectifier.



Step 2: Pick L1. Either set L1 = 0 (in which case C2 isn't needed) or pick L1 so that it's impedance is more than RL at 60Hz.

Assume L1 reduces the ripple at V2 by 3x. This means

$$|j\omega L_1| \approx 3 \cdot R_L$$

$$L_1 \approx 795.7mH$$

These are not available from Digikey, so use a C-24X inductor from Digikey:

L1 = 1H

R1 = 50 Ohms (from the data sheets)

(note: Ideally we want R1 = 0. Inductors have a DC resistance, however, like it or not.)

Step 3: Determine C1 to set the ripple at V1 to 1Vpp

The current, I1, is

$$\max(V_1) = 19.3V$$

$$I_1 \approx \frac{19.3V}{150\Omega} = 128.7mA$$

This produces a ripple of

$$I_1 = C_1 \frac{dV_1}{dt}$$

$$128.7mA = C_1 \frac{1V_{pp}}{1/60s}$$

$$C_1 = 2144\mu F$$

Step 4: Determine C2 to set the ripple at V2 to 100mVpp

Assume C2 = 0. The ripple at V2 will be

$$V_2 = \left(\frac{100}{100+(50+j377)}\right) 1V_{pp}$$

$$V_2 = 246.5mV_{pp}$$

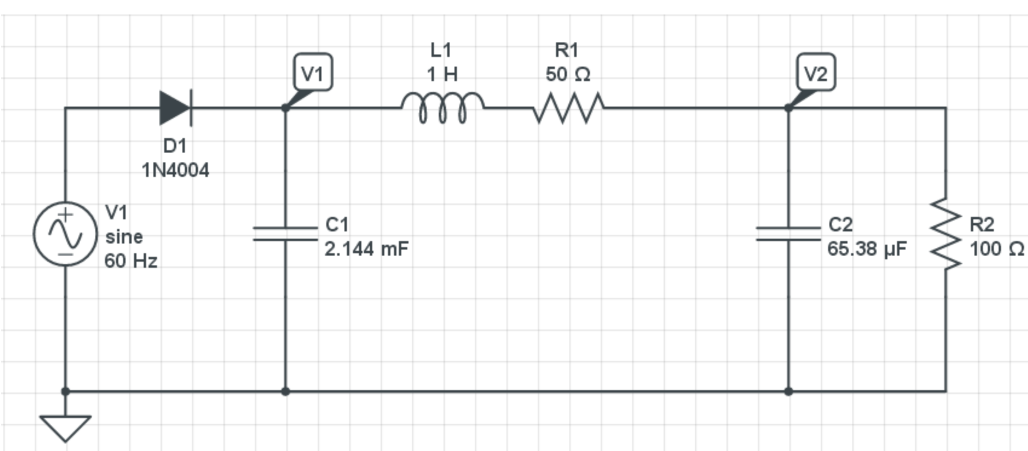
To reduce the ripple down to 100mVpp, C2 needs to have an impedance that is 2.465 times smaller than RL

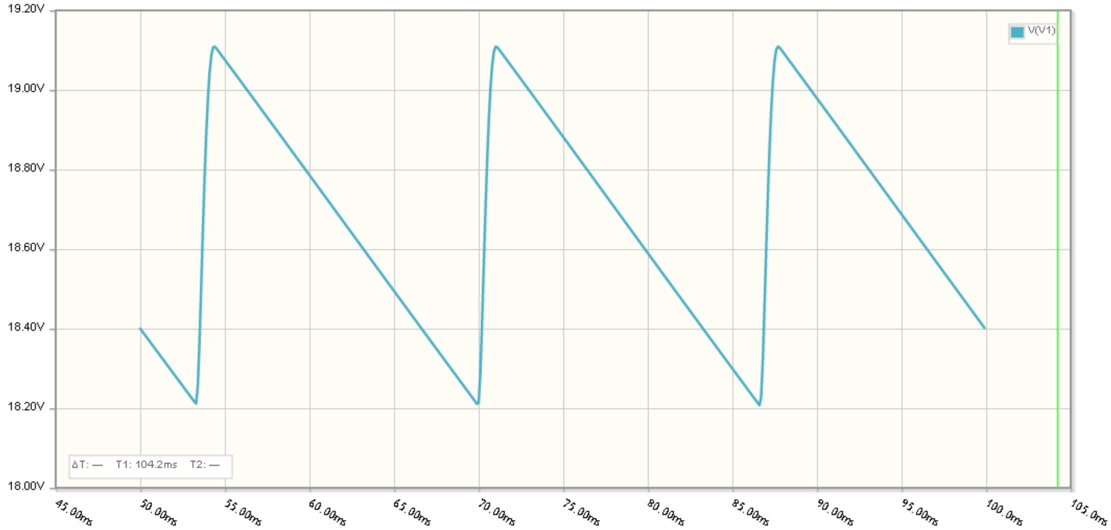
$$Z_c = \left(\frac{100mV_{pp}}{246.5mV_{pp}}\right) \cdot 100\Omega$$

$$Z_c = 40.57\Omega = \left|\frac{1}{j\omega C_2}\right|$$

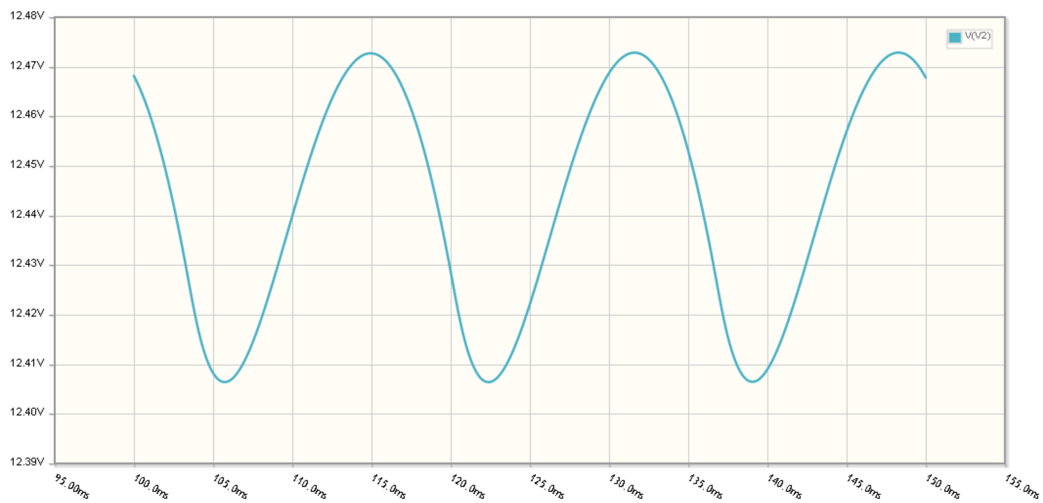
$$C_2 = 65.38\mu F$$

Checking in CircuitLab





V1(t): Ripple = 900mVpp (vs. 1Vpp target)



V2(t): Ripple = 60.0mVpp (vs. 100mVpp target)

If you *really* wanted 100mVpp, scale C2 proportionately

$$C_2 \rightarrow \left(\frac{60.0mV_{pp}}{100mV_{pp}}\right) 65.38\mu F = 39.23\mu F$$