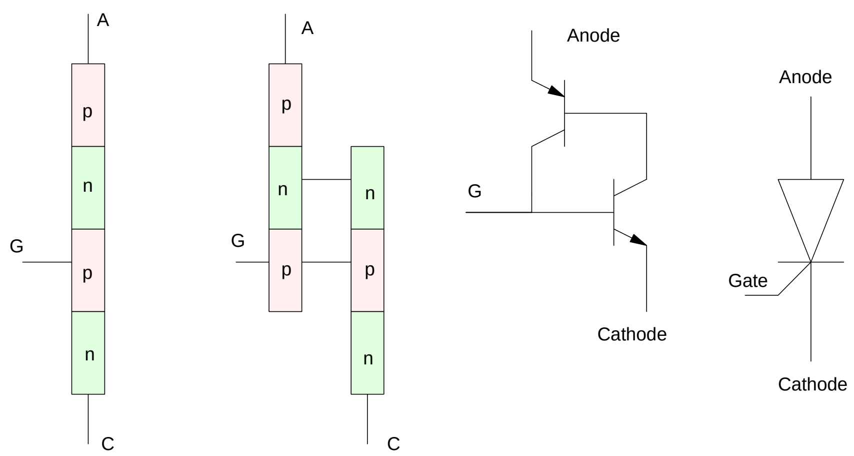
Semiconductor Relays (SCR)

AC to DC Conversion (take 2)

Thyristor (SCR):

A thyristor (or SCR) is a PNPN device, which can be thought of as a PNP and an NPN transistor strung together:

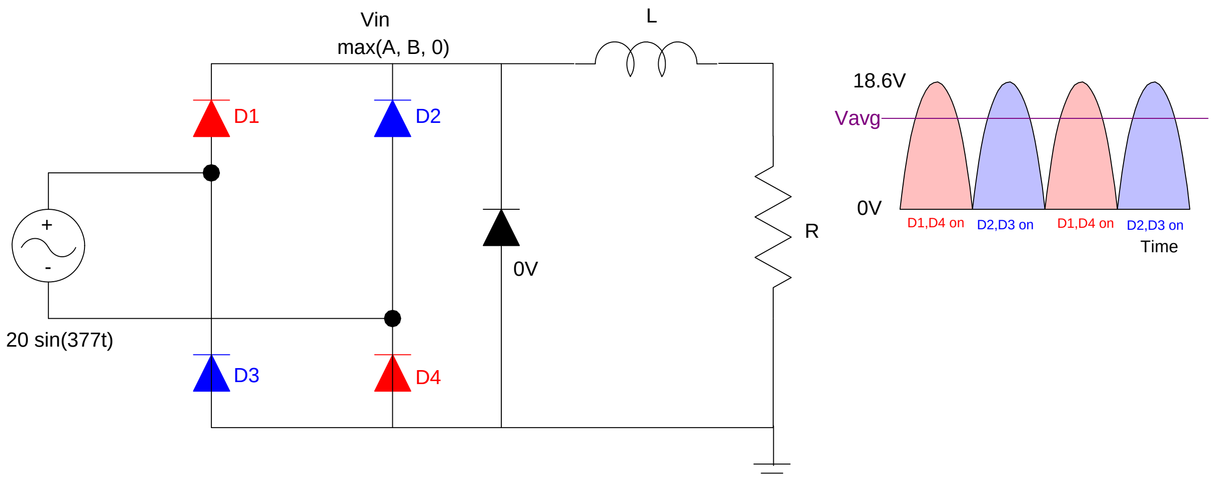


This creates a bistable switch. For example, assume the anode is at +Va and the cathode is 0V.

- Assume the current is zero (the thyristor is off) and the gate is floating. An n-p junction blocks all current flow.
- Assume a voltage is applied at the gate to turn on the NPN transistor. Current flows from the base to the emitter of the NPN transistor, turning it on. This drops the voltage on the collector. This in turn is connected to the base of the PNP transistor, turning it on as well. Both transistors turn on and current flows from the anode to the cathode.
- If the gate voltage is removed so the gate floats, the thyristor remains on.
- To turn off the thyristor, ground the gate. This turns off the diode in the NPN transistor, halting all current flow.
- If the gate voltage is removed so the gate floats, the thyristor remains off.

AC to DC Converter:

One use of a SCR is to allow you to adjust the output of a DC to AC converter. The idea is that if you use 'normal' diodes in a full-wave rectifier such as the following:



Four diodes creating a full-wave rectifier. A 5th diode is added for the SCR (coming soon...)

The average voltage across the load is

$$V_{avg} = \frac{1}{\pi}\int_0^{\pi} V_p \sin(t) \cdot dt$$

$$V_{avg} = \frac{2}{\pi} \cdot V_p = 0.6366 V_p$$

If the load is a motor, the average voltage applied to the motor is 0.6366 times the peak voltage.

If the top two diodes are replaced with SCR's and these are pulsed at θ degrees (termed the firing angle), the top SCR's don't conduct until they are pulsed. The resulting voltage at the output is less than before. The average voltage in this case would be

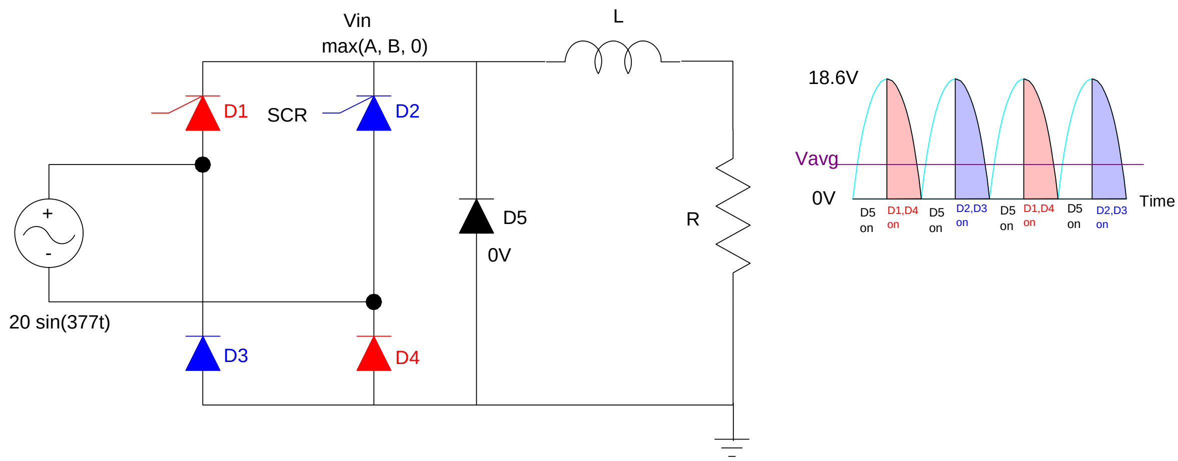
$$V_{avg} = \frac{1}{\pi}\int_{\theta}^{\pi} V_p \sin(t) \cdot dt$$

$$V_{avg} = \frac{V_p}{\pi} \cdot (-\cos(t))_{\theta}^{\pi}$$

$$V_{avg} = \frac{V_p}{\pi} \cdot (1 + \cos(\theta))$$

Note: This is a little bit off since V1 is equal to -0.7V while diode D5 is on. To take this into account, shift V1 by 0.7V resultsing in

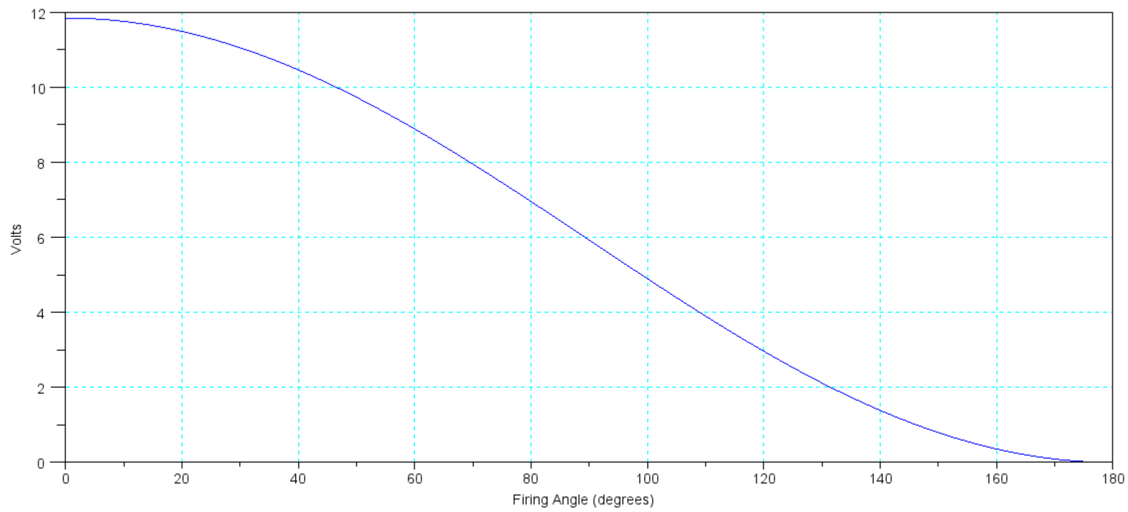
$$V_{avg} = \left(\frac{V_p + 0.7}{\pi}\right) \cdot (1 + \cos(\theta)) - 0.7$$



By using SCR's, the average voltage to the load can be reduced by adjusting the firing angle.

in MATLAB, the average voltage vs. fiding angle is:

```
q = [0:0.01:180]';
Vavg = (18.4 + 0.7) / pi * (1 + cos(q*pi/180)) - 0.7;
plot(q,Vavg);
```



Average Voltage vs. Firing Angle

An SCR likewise provides a easy way to convert from AC to DC, allowing you to adjust the effective voltage to the load by adjusting the firing angle. "Easy" way, that is, if you can control the firing angle (the timing that a pulse is sent to the SCR to turn it on). With microcontrollers operating at 10MHz plus costing less than $3 each, this is fairly easy to do.

To illustrate how easy this is to do and how precise the voltage can be controlled, assume a PIC processor running at 10MHz is used to turn on the SCR's. A 60Hz sine wave cycles through 180 degrees every 8.33ms.

$$t = \frac{1}{2} \cdot \frac{1}{60} = 0.00833$$

8.333ms corresponds to 83,333 clocks:

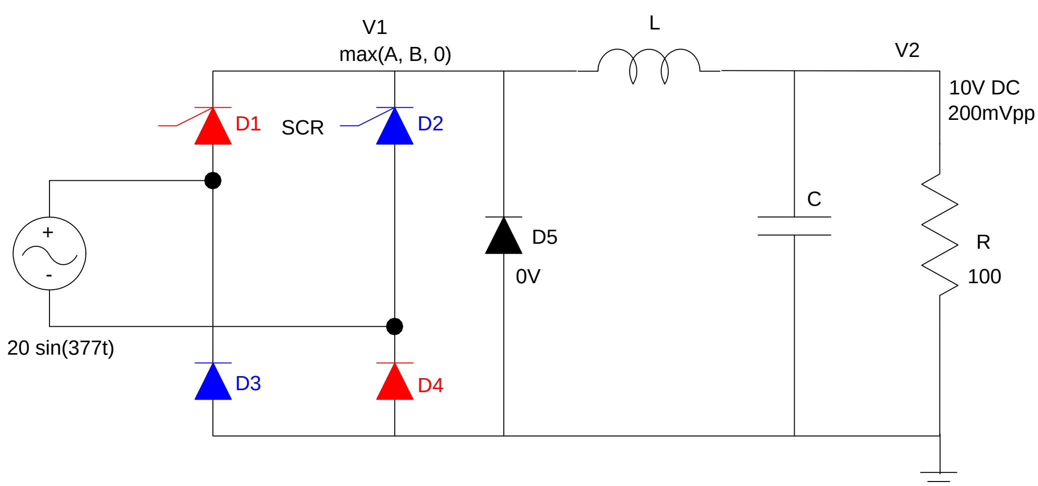
$$N = \left(10,000,000\frac{\text{clocks}}{\text{second}}\right)(0.00833 \text{ seconds}) = 83,333$$

A $3 processor such as a PIC can control the firing angle (and hence the AC to DC voltage) with a resolution of one part in 83,333. With a peak voltage of $V_p = 18.6V$, the resolution is 0.2mV (!).

$$resolution = \frac{18.6V}{83,333} = 223\mu V$$

AC to DC Design Example: Design a circuit to convert 20Vp 60Hz AC to 10VDC capable of driving a 100 Ohm load with 500mVpp ripple.

Just like before, you can choose L to reduce the ripple at the load (R). If you want to reduce the ripple even more, add a capacitor just like we did with a Buck regulator.



AC to DC Converter Design Example

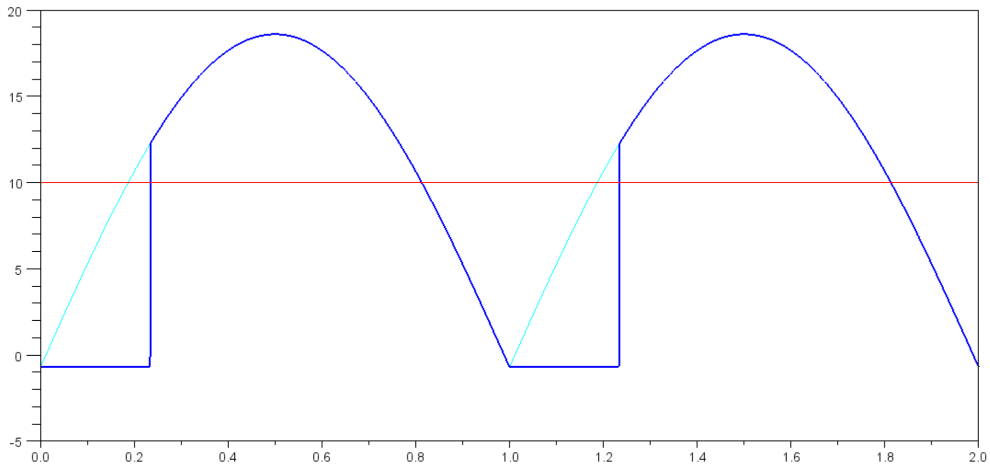
Solution: First, find the firing angle. Note that the 20V peak will actually be 1.4V less (18.6V) due to the voltage drop across two diodes

$$avg(V_{load}) = \left(\frac{V_p+0.7}{\pi}\right) \cdot (1 + \cos(\theta)) - 0.7$$

$$10V = \frac{19.3}{\pi} \cdot (1 + \cos(\theta)) - 0.7$$

$$\theta = 42.12^0$$

The signal at V1 is going to look like the following:



Signal at V1: 18.6Vp Rectified Sine Wave (cyan), Signal at V1 with a firing angle of 42.12 degrees (blue), and the 10VDC average voltage (red)

The DC signal will go straight to the load

avg(V2) = avg(V1) = 10VDC.

The AC signal will be attenuated by the inductor and the capacitor. First, choose the inductor.

The ripple at V1 is 19.3Vpp:

- The maximum of V1 is 18.6V
- The minimum of V1 is -0.7V (when diode D5 turns on)
- The peak-to-peak ripple is then 19.3Vpp

Pick L to reduce this ripple by a factor of 10x. To do this, pick L so that its impedance at 120Hz is ten times the impedance of R

$$\omega L = 10R$$

$$(2\pi \cdot 120Hz) \cdot L = 10 \cdot 100\Omega$$

$$L = 1.32H$$

This reduces the ripple at V2 to 1.93Vpp

Pick C to reduce this ripple down to 500mVpp. To do this, pick C so that its impedance is 3.86 times smaller than R

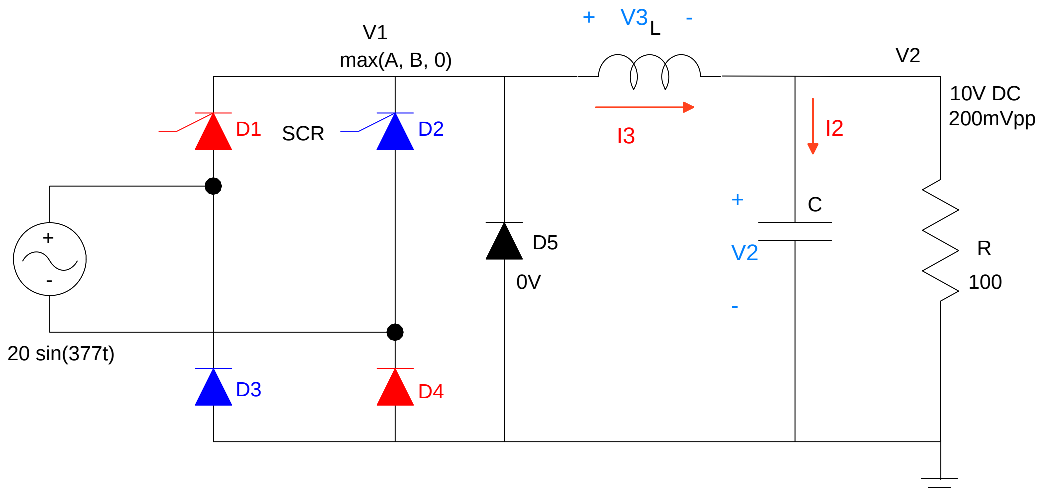
$$\frac{1}{\omega C} = \frac{0.5V_{pp}}{1.93V_{pp}} \cdot 100\Omega$$

$$\frac{1}{\omega C} = 25.9\Omega$$

$$C = 102\mu F$$

Matlab Simulation

Given the circuit, you can simulate the voltage at V2 by writing the differential equations that describe this circuit and solving numerically.



Start with assuming V1 is given (the clipped sine wave from before).

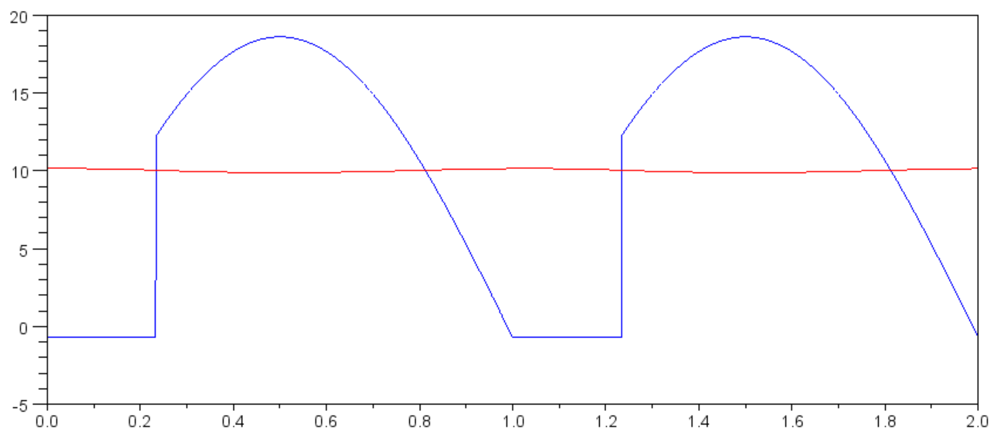
Define the state variables to be the current through the inductor (I3) and the voltage across the capacitor (V2).

Write the differential equations for each:

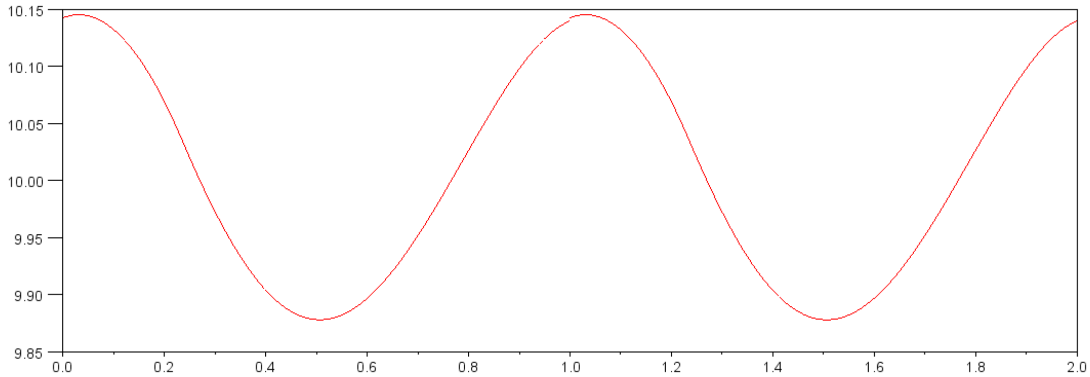
$$V_3 = L\dot{I}_3 = V_1 - V_2$$

$$I_2 = C\dot{V}_2 = I_3 - \frac{V_2}{R}$$

Solve using Matlab



Voltage at V1 (blue) and V2 (red)

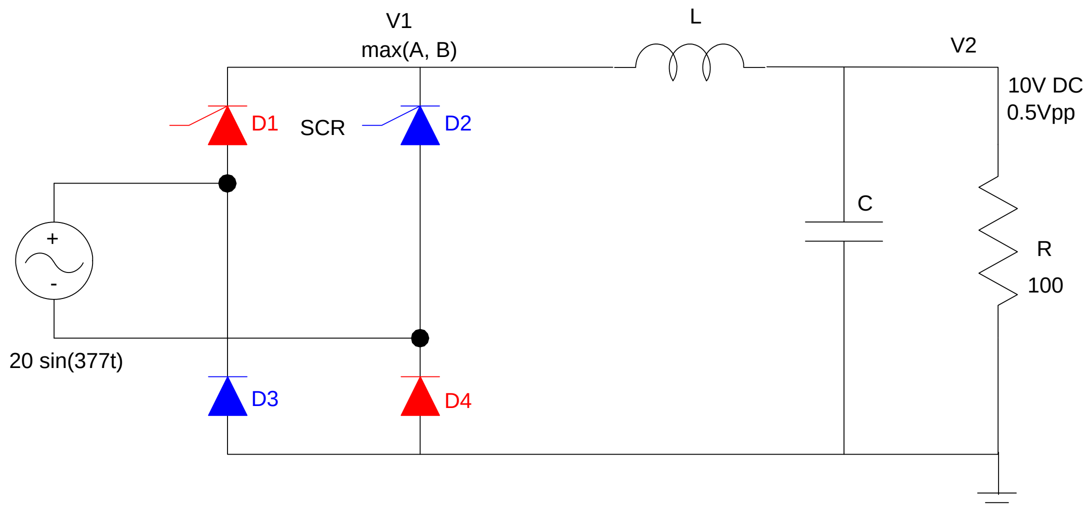


Voltage at V2: DC = 10.00V, AC = 267mVpp

Matlab Code:

```
t = [0:0.001:1]';
dt = ( t(2) - t(1) ) / 120;

V1 = 19.3*sin(t*pi) .* (t > 42.12 /180)  -  0.7*(t < 42.12/180);

V2 = 0*t;
I3 = 0*t;
npt = length(t);

C = 102e-6;
R = 100;
L = 1.32;

for n=1:40

   V2(1) = V2(npt);
   I3(1) = I3(npt);

   for i=1:npt-1
      dV2 = ( I3(i) - V2(i)/R ) / C;
      dI3 = ( V1(i) - V2(i) ) / L;

      V2(i+1) = V2(i) + dV2 * dt;
      I3(i+1) = I3(i) + dI3 * dt;
      end

   plot(t,V1,t,V2);
   end

plot(t,V2);
```

AC to DC Converter (take 3)



Variation on the SCR AC to DC Converter: diode D5 is removed. This results in V1 going negative

You actually don't need diode D5 for the AC to DC converter. If you remove this diode, however, the voltage at V1 changes from

$$V_1 = \max(A, B, 0V)$$

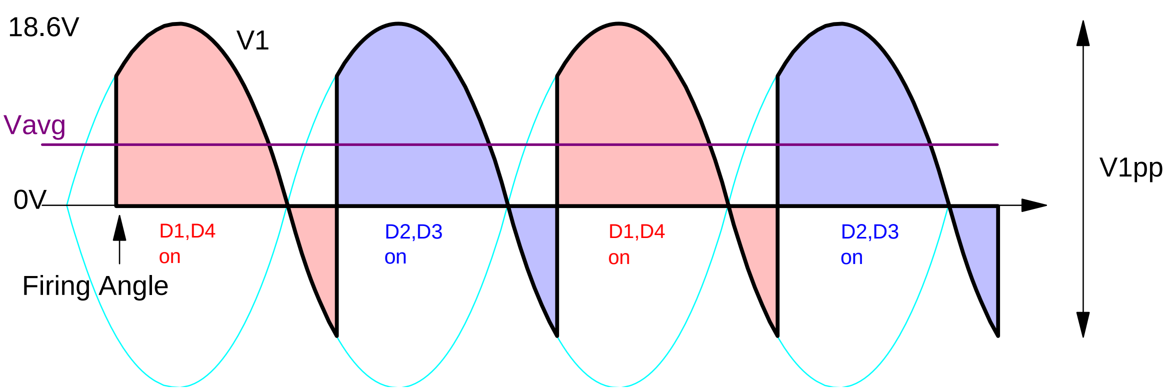
to

$$V_1 = \max(A, B)$$

If the voltage at A goes negative and B hasn't turned on yet, then

$$V_1 = \max(A) = A$$

V1 can actually go negative. This results in the signal at V1 will look something like the following:



Signal at V1 with only 4 diodes in the AC to DC converter. A firing angle of 30 degrees shown.

In this case, the average voltage with a firing angle of θ will be

$$V_{avg} = \frac{1}{\pi} \cdot V_p \cdot \int_{\theta}^{\pi+\theta} \sin(t)dt$$

$$V_{avg} = \frac{1}{\pi} \cdot V_p \cdot (\cos(t))_{\theta}^{\pi+\theta}$$

$$\boxed{V_{avg} = \frac{2}{\pi} \cdot V_p \cdot \cos(\theta)}$$

The peak-to-peak ripple will then be

$$V_{1pp} = \max(V_1) - \min(V_1)$$

$$V_{1pp} = V_p - V_p \sin(\pi + \theta)$$

$$V_{1pp} = V_p + V_p \sin(\theta)$$

$$\boxed{V_{1pp} = V_p \cdot (1 + \sin(\theta))}$$

AC to DC Design Example (take 2): Design a circuit to convert 20Vp 60Hz AC to 10VDC capable of driving a 100 Ohm load with 500mVpp ripple.

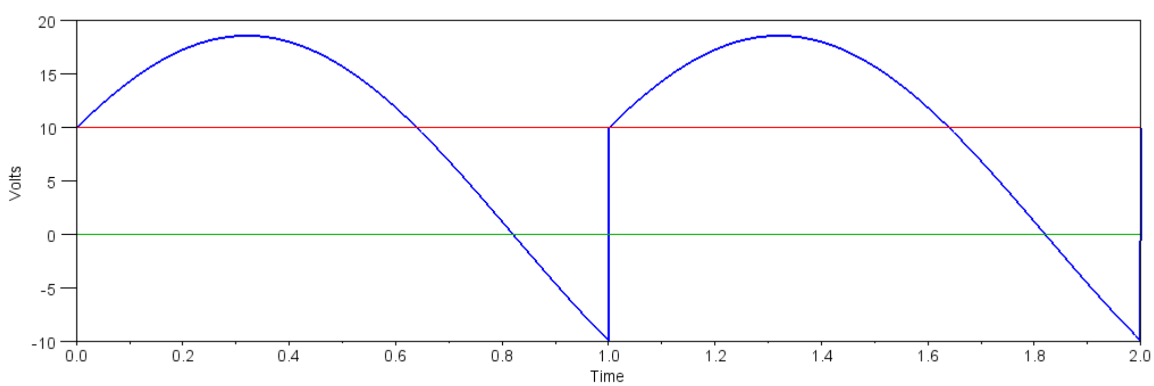
For 10VDC:

$$V_{avg} = \frac{2}{\pi} \cdot V_p \cdot \cos(\theta)$$

$$10V = \frac{2}{\pi} \cdot 18.6 \cdot \cos(\theta)$$

$$\theta = 32.38^0$$

The signal at V1 then looks like the following:



Signal at V1 with a firing angle of 32.38 degrees. avg(V1) = 10.00V.

The DC signal goes to the load unchanged (the inductor and capacitor have no effect at DC)

avg(V2) = 10V

The AC signal (120Hz) is attenuated by the inductor and the capacitor. The peak-to-peak voltage at V1 is

$$V_{1pp} = \max(V_1) - \min(V_1)$$

$$V_{1pp} = 18.6V - (-9.91V)$$

$$V_{1pp} = 28.51V_{pp}$$

Pick L to reduce this ripple by 10x (down to 2.851Vpp)

$$\omega L = 10R$$

$$(2\pi \cdot 120Hz)L = 1000\Omega$$

$$L = 1.32H$$

Pick C to reduce this by another factor of 5.7 to bring the ripple down to 0.5Vpp

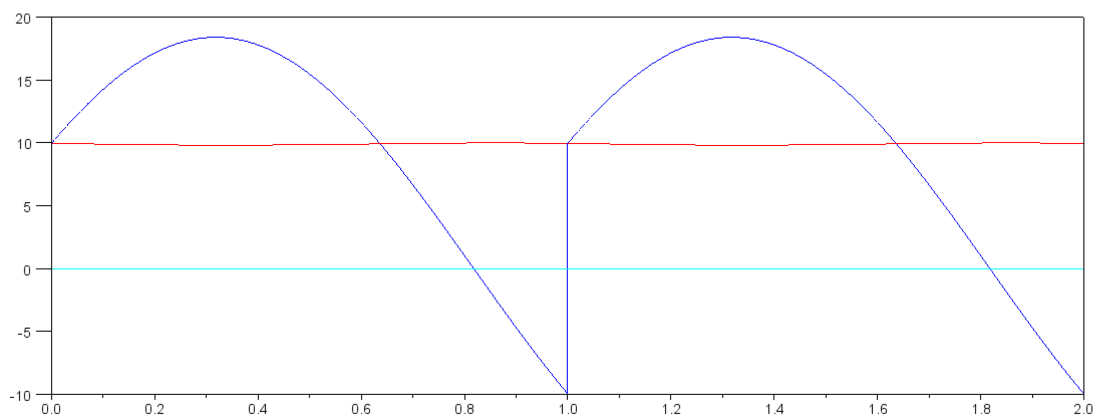
$$\frac{1}{\omega C} = \frac{0.5V_{pp}}{2.851V_{pp}} \cdot 100\Omega$$

$$\frac{1}{\omega C} = \frac{1}{5.7} \cdot 100\Omega$$

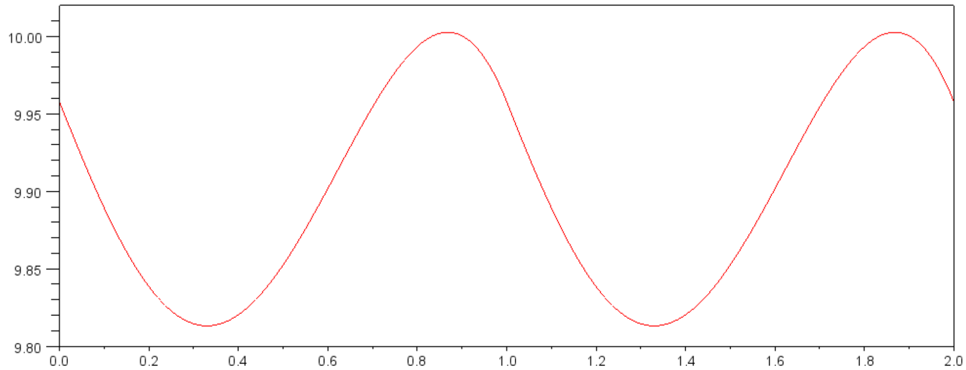
$$\frac{1}{\omega C} = 17.5\Omega$$

$$C = 151\mu F$$

Matlab Simulation



Voltage at V1 (blue) and V2 (red)



Votlage at V2: DC = 9.90V, AC = 190mVpp

Matlab Smulation:

```
t = [0:0.001:1]';
dt = ( t(2) - t(1) ) / 120;

V1 = 18.4*sin(t*pi  + 32.38*pi/180);

V2 = 0*t;
I3 = 0*t;
npt = length(t);

C = 151e-6;
R = 100;
L = 1.32;

for n=1:40

   V2(1) = V2(npt);
   I3(1) = I3(npt);

   for i=1:npt-1
      dV2 = ( I3(i) - V2(i)/R ) / C;
      dI3 = ( V1(i) - V2(i) ) / L;

      V2(i+1) = V2(i) + dV2 * dt;
      I3(i+1) = I3(i) + dI3 * dt;
      end

   plot(t,V1,t,V2);
   end

plot(t,V2);
```