Semiconductor Relays (SCR)

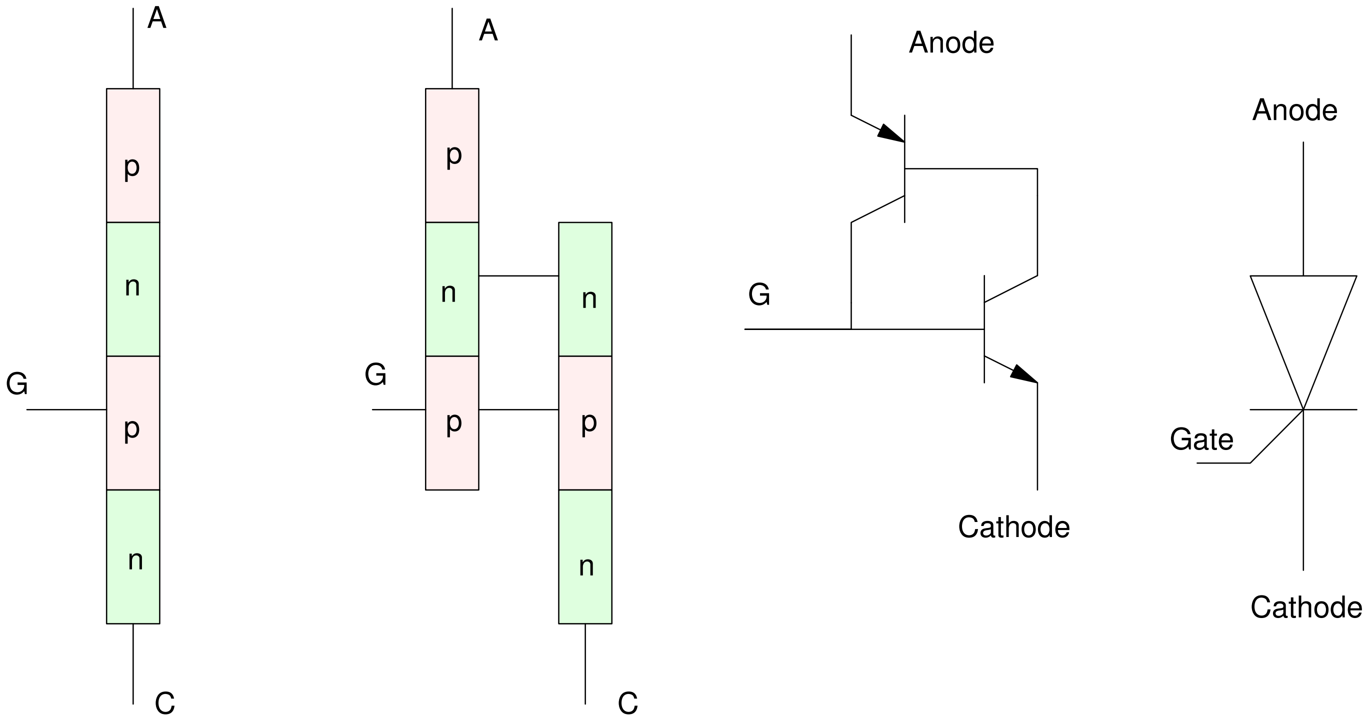
ECE 320 Electronics I

Jake Glower - Lecture #18

Please visit Bison Academy for corresponding
lecture notes, homework sets, and solutions

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.

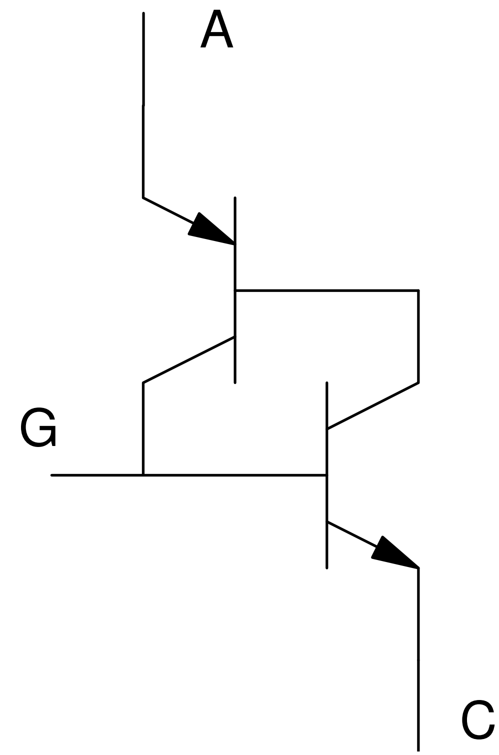
- Off: Ib = 0
- Once off, it remains off

Apply a small current to the gate

- This turns on the NPN
- This turn on the PNP
- Once on, it remains on

Acts like a diode

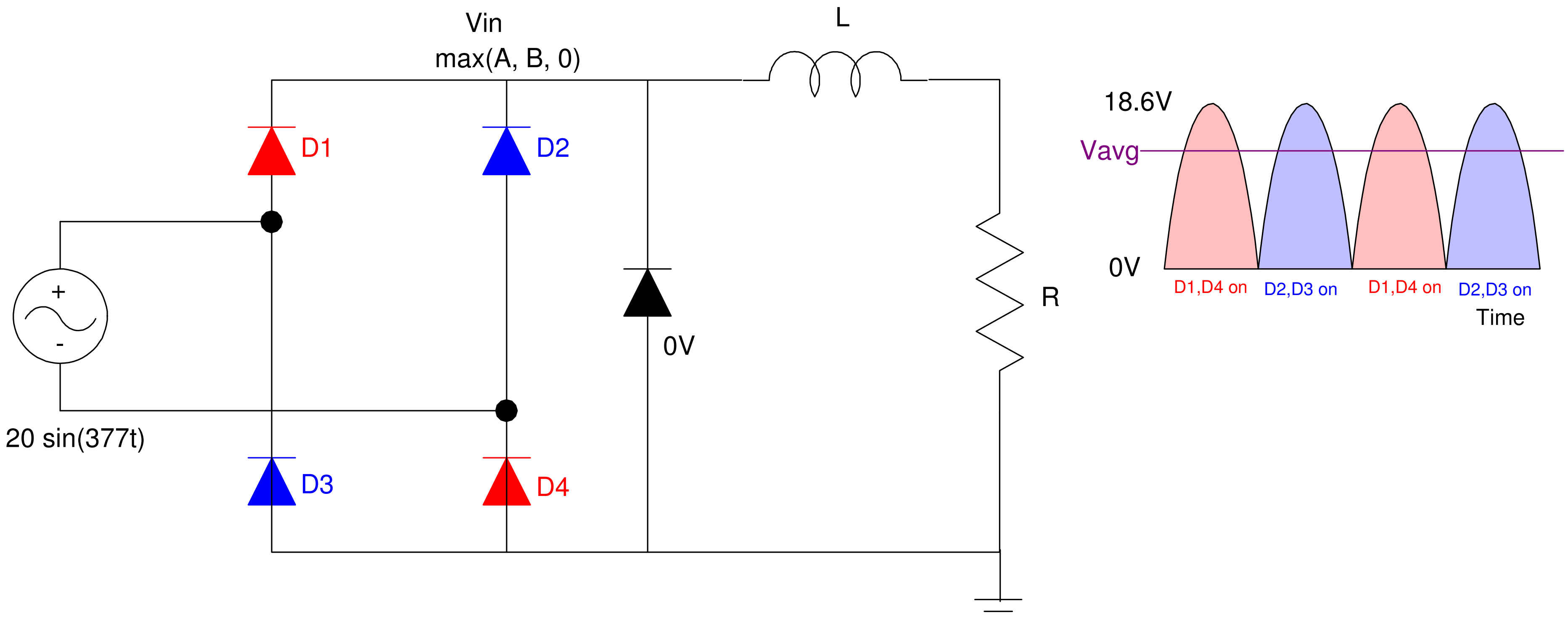
- Ig turns it on



AC to DC Converter:

SCR's allow you to adjust the DC level of an AC to DC converter

- Firing Angle = 0 degrees
- Vavg = 0.6366 Vp

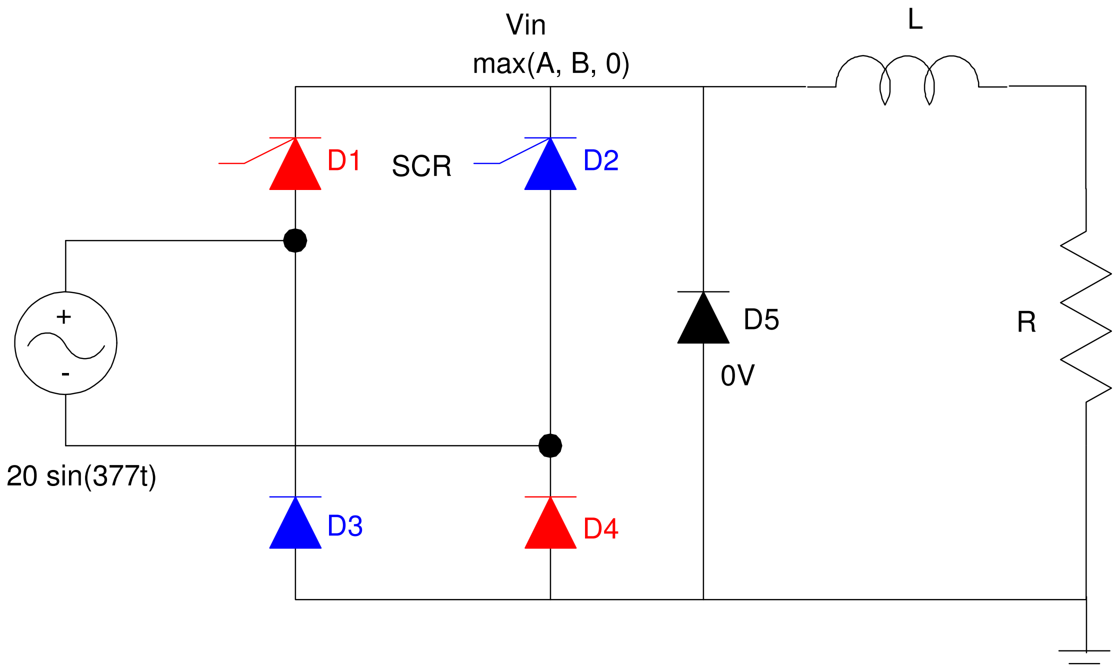


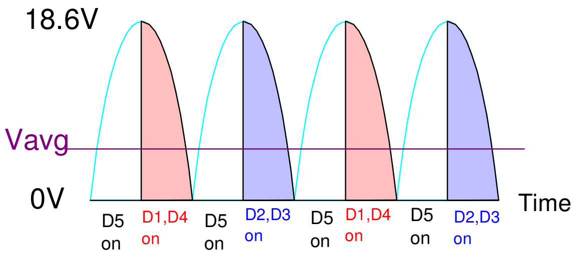
Four diodes creating a full-wave rectifier. A 5th diode is added for the SCR (coming soon...)

Firing Angle = θ

$$V_{avg} \approx \frac{1}{\pi}\left(\int_0^{\theta} (-0.7)\cdot dt + \int_{\theta}^{\pi} (V_p \cdot \sin(t) - 1.4)\cdot dt\right)$$

$$V_{avg} \approx \left(\frac{V_p}{\pi}\right)\cdot(1+\cos(\theta)) - 0.7\left(2 - \frac{\theta}{180^0}\right)$$

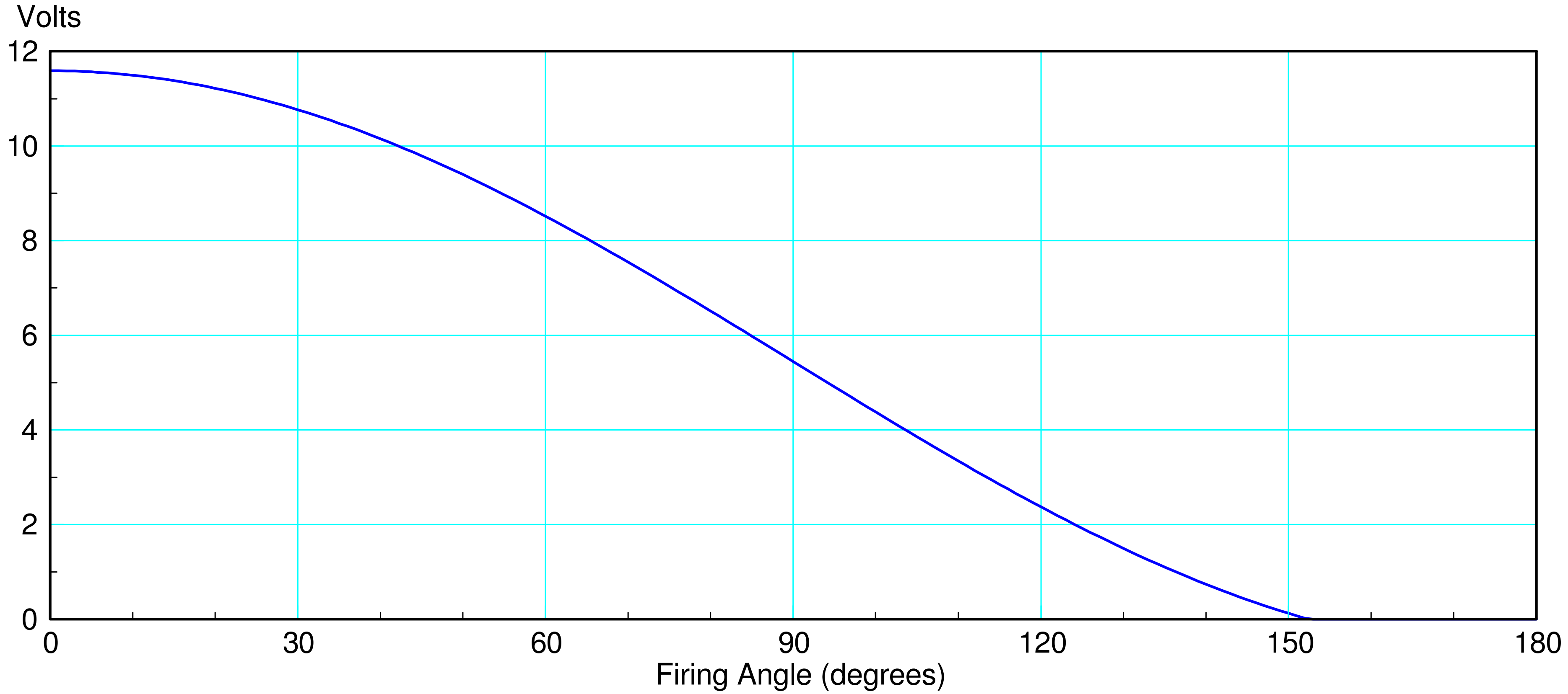




By using SCR's, the average voltage to the load can be reduced by adjusting the firing angle.

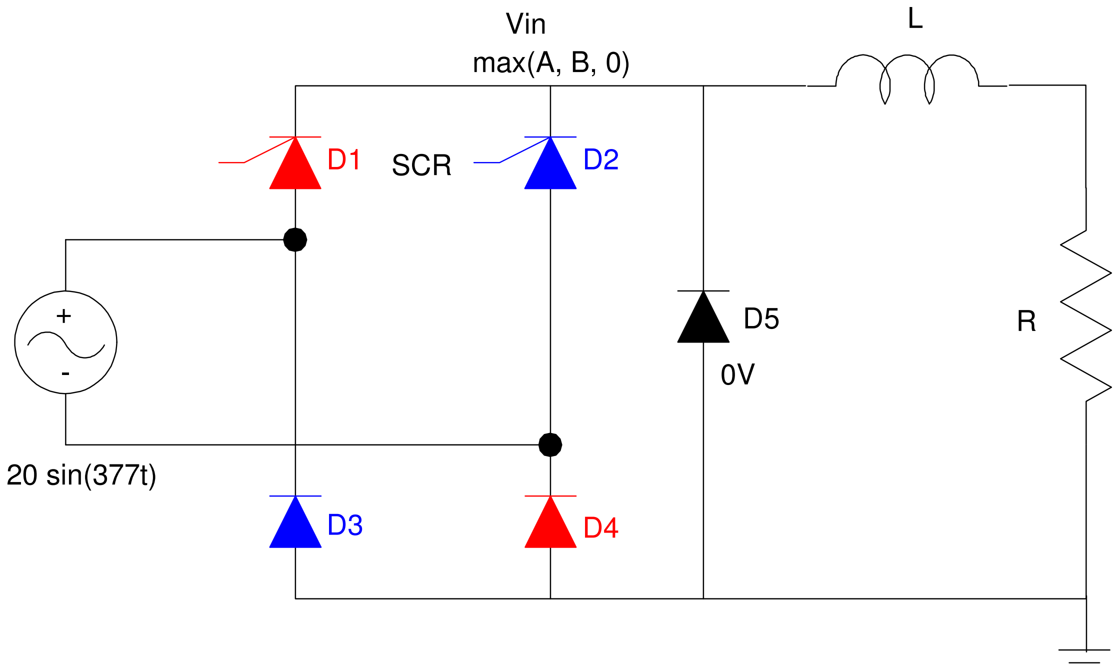
Firing Angle vs. Voltage

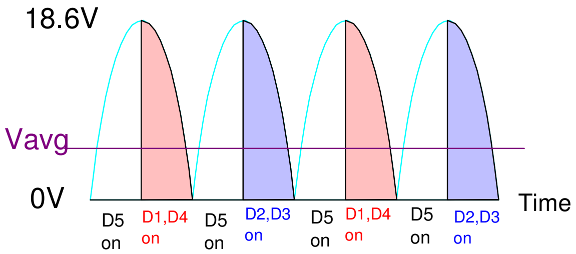
```
q = [0:0.01:180]';
Vavg = (20 / pi) * (1 + cos(q*pi/180)) - 0.7*(2 - q/180);
plot(q,Vavg);
```



Resolution:

- 180 degrees = 8.333ms (60Hz)
- 1 clock = 100ns (PIC18F4620)
- Able to control the DC voltatge to 1 part in 83,333





SCR Analysis

Determine the voltages at V1 and V2

- 20Vp 60Hz AC source
  - 18.6Vp at V1 (lose 1.4V through two diodes)
- 45 degree firing angle

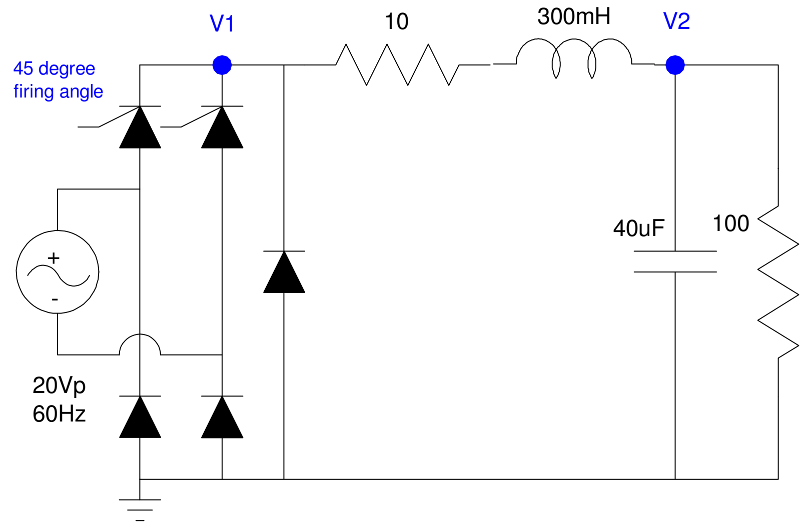
DC Analysis

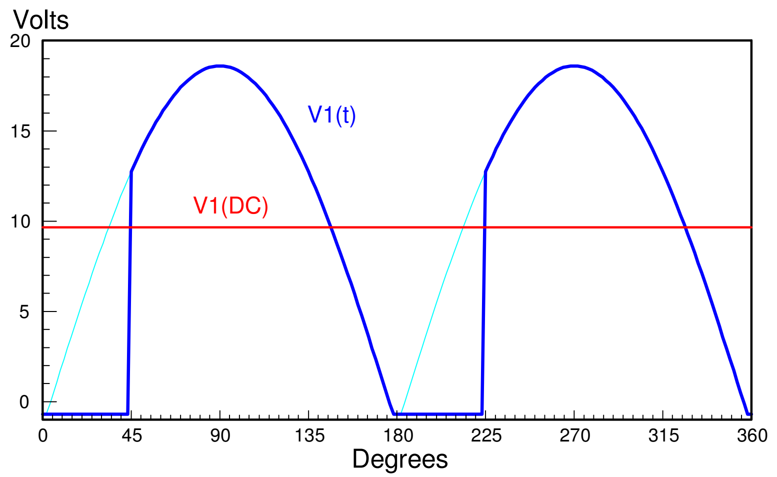
$$V_1(DC) = \left(\frac{20V}{\pi}\right) \cdot (1 + \cos(45^0)) - 0.7\left(2 - \frac{45^0}{180^0}\right)$$

$$V_1(DC) = 9.643V$$

$$V_2(DC) = \left(\frac{100}{100+10}\right) \cdot 9.643$$

$$V_2(DC) = 8.766V$$





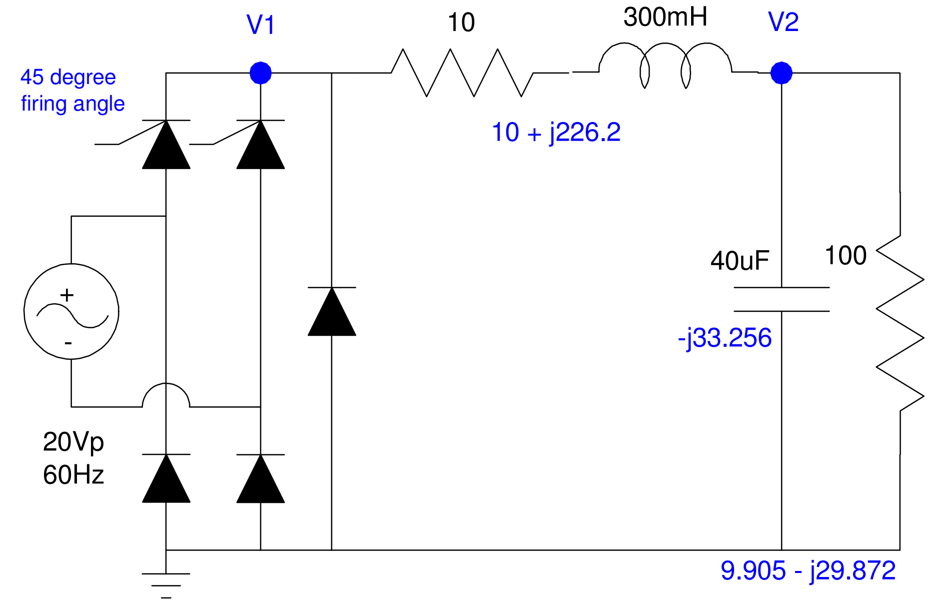
AC Analysis (take 1)

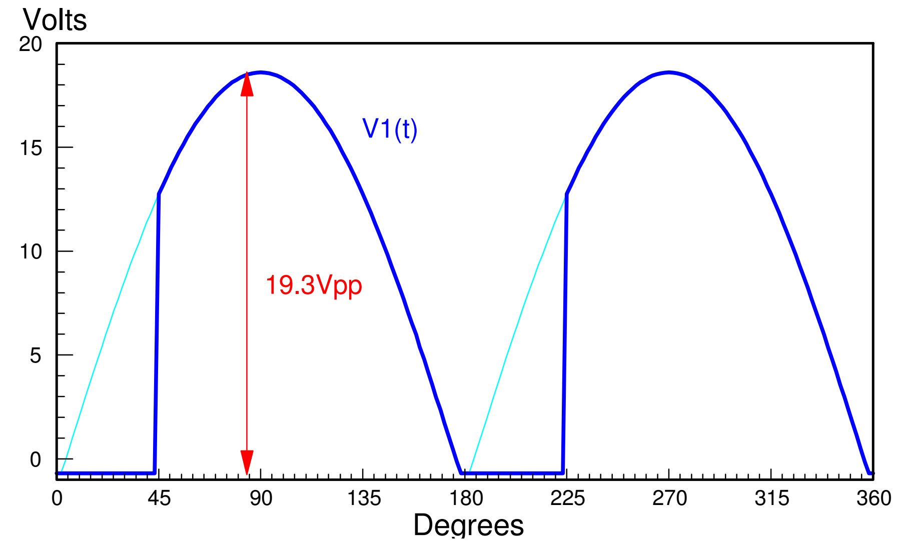
$$V_1(AC) \approx 18.6V - (-0.7V)$$

$$V_1(AC) \approx 19.3V_{pp}$$

$$V_2(AC) = \left(\frac{(9.905 - j29.872)}{(9.905 - j29.872) + (10 + j226.2)}\right) \cdot 19.3V_{pp}$$

$$|V_2(AC)| = 2.365V_{pp}$$





note:

- Only the magnitude matters
- Phase tells you V2 is out of phase from V1
- We don't care

AC Analysis (take 2)

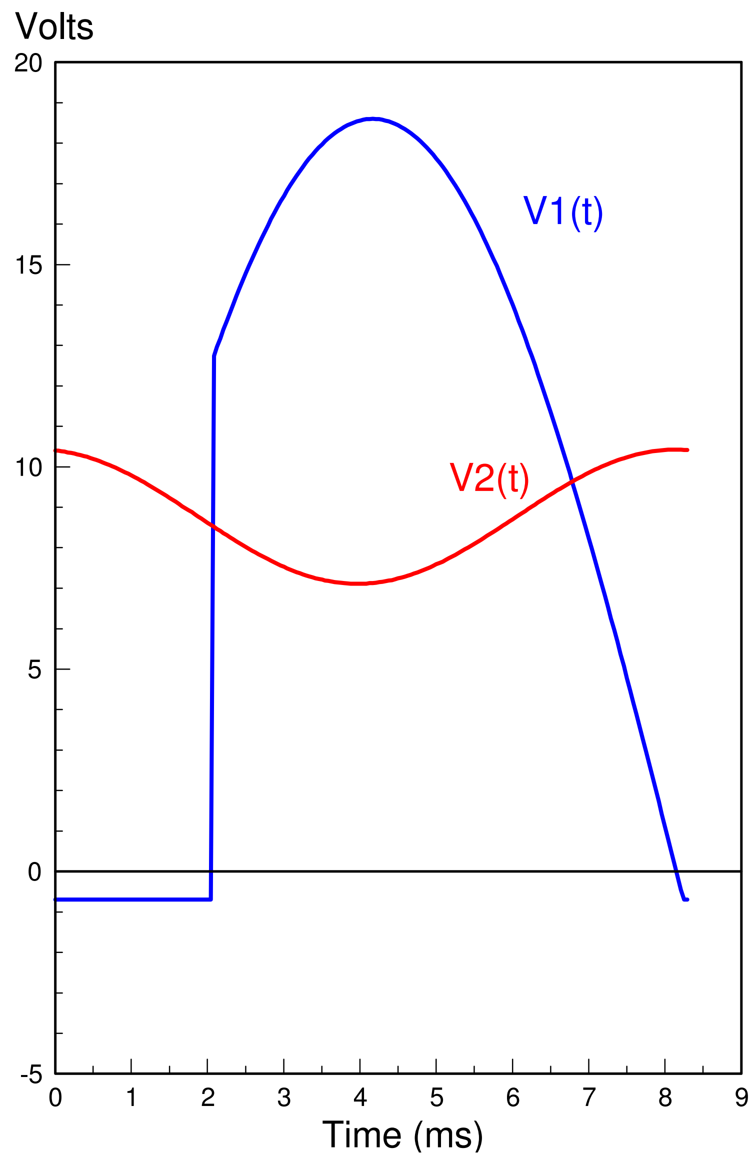
Use the first 2-terms of the Fourier tansform

- DC + 120Hz
  - 45 degrees: the first 250 points (of 1000) are -0.7V

```
t = [0:0.001:1]';
V1 = max(-0.7,  20*sin(pi*t) - 1.4);
V1(1:250) = -0.7;    % 45 degrees

V1DC = mean(V1)
    V1DC = 9.6431       vs. 9.6428V
V2DC = (100/110)*V1DC
    V2DC = 8.7664       vs. 8.7662V

V1p = 2*mean(V1 .* exp(-j*2*pi*t));
V1pp = 2*abs(V1p)
    V1pp = 20.7625   % vs. 19.3V
```

$$V_{2pp} = \left| \frac{(9.905 - j29.872)}{(9.905 - j29.872) + (10 + j226.2)} \right| \cdot V_{1pp}$$

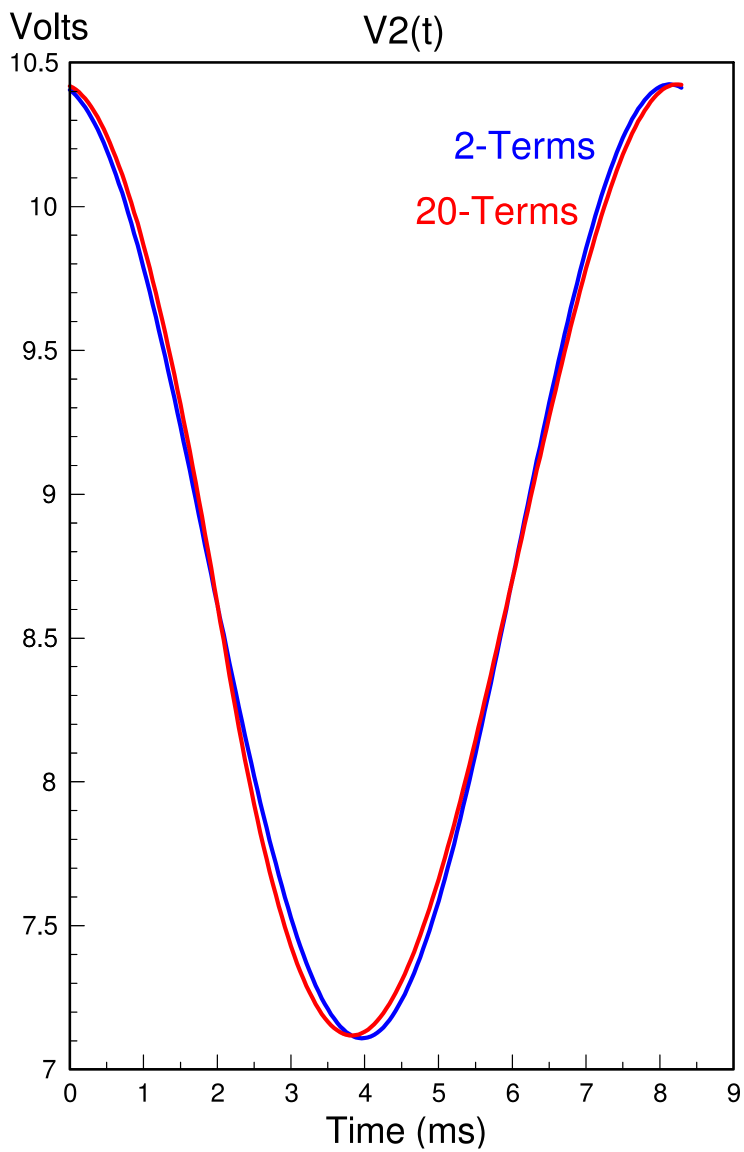
```
    V2pp =  2.5440Vpp    % vs. 2.365Vpp
```



AC Analysis (take 3)

- Fourier Transform out to the 20th harmonic
- Only slightly better than 2-term approximation

	V2(DC)	V2(AC)
V1(AC) = 19.3Vpp	8.7664 V	2.365 Vpp
Fourier DC + 120Hz	8.7664 V	2.5440 Vpp
Fourier 20-terms	8.7664 V	2.5840 Vpp
CircuitLab (coming soon)	8.898 V	3.292 Vpp

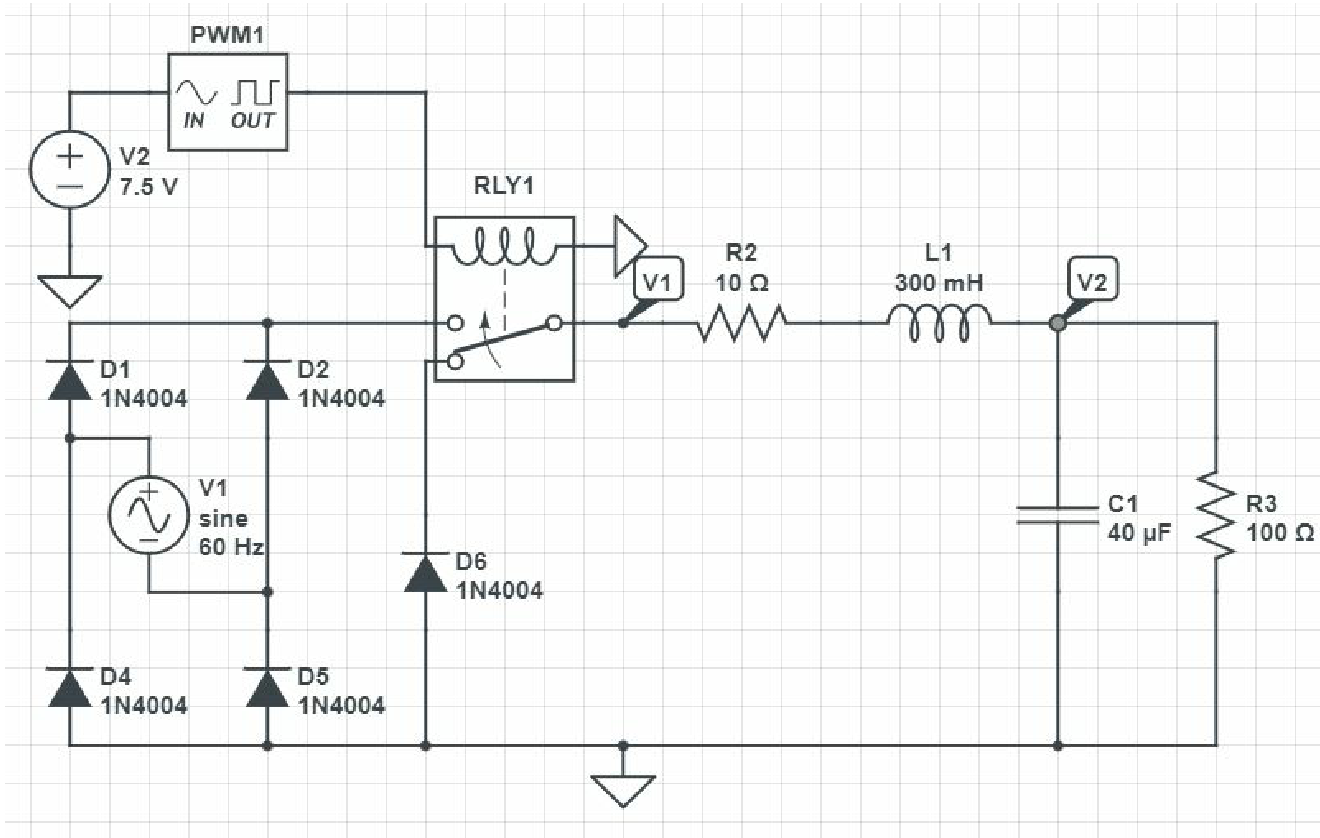


CircuitLab Simulation

SCR's are currently not working

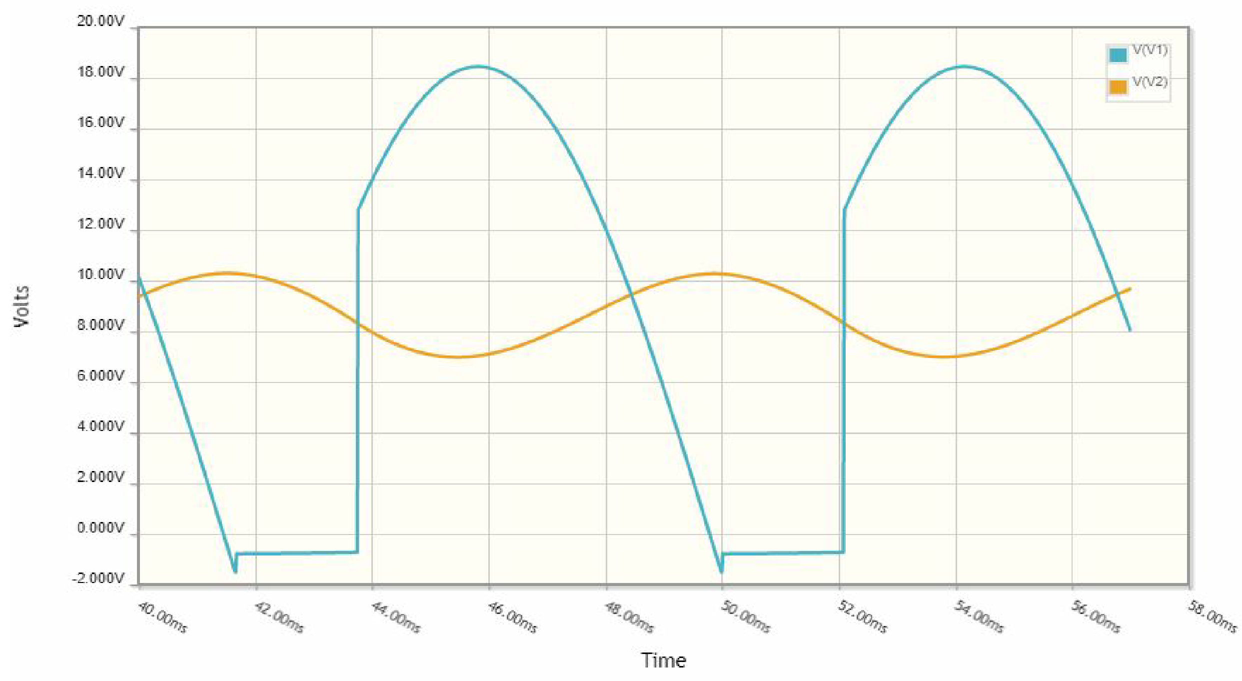
Approximate it with

- A relay
- 120Hz PWM
- 75% on (25% off) = 45 degree firing angle



CircuitLab Simulation Result

- V1 = blue
- V2 = orange
- max(V2) = 10.27V
- min(V2) = 6.978V



V2(DC) = (max + min) / 2

- V2(DC) = 8.624V
- vs. 8.898V calculated

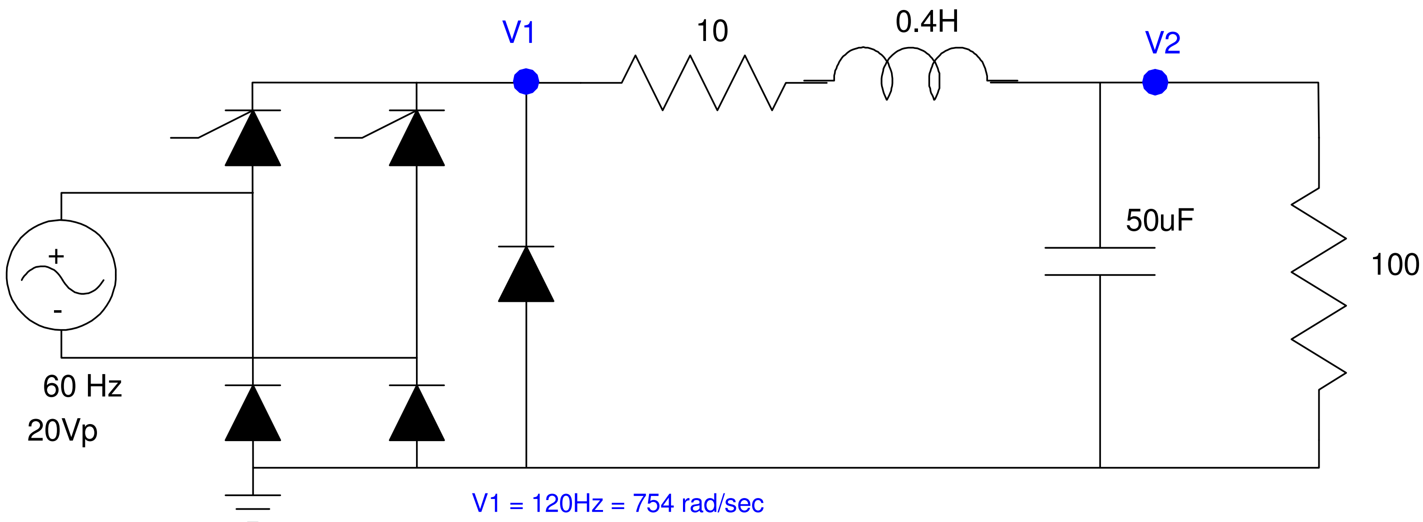
V2(AC) = (max - min)

- V2(AC) = 3.292Vpp
- vs. 2.365Vpp calculated

Handout:

Determine the voltage at V1 and V2 (both DC and AC).

- Assume a firing angle of 25 degrees

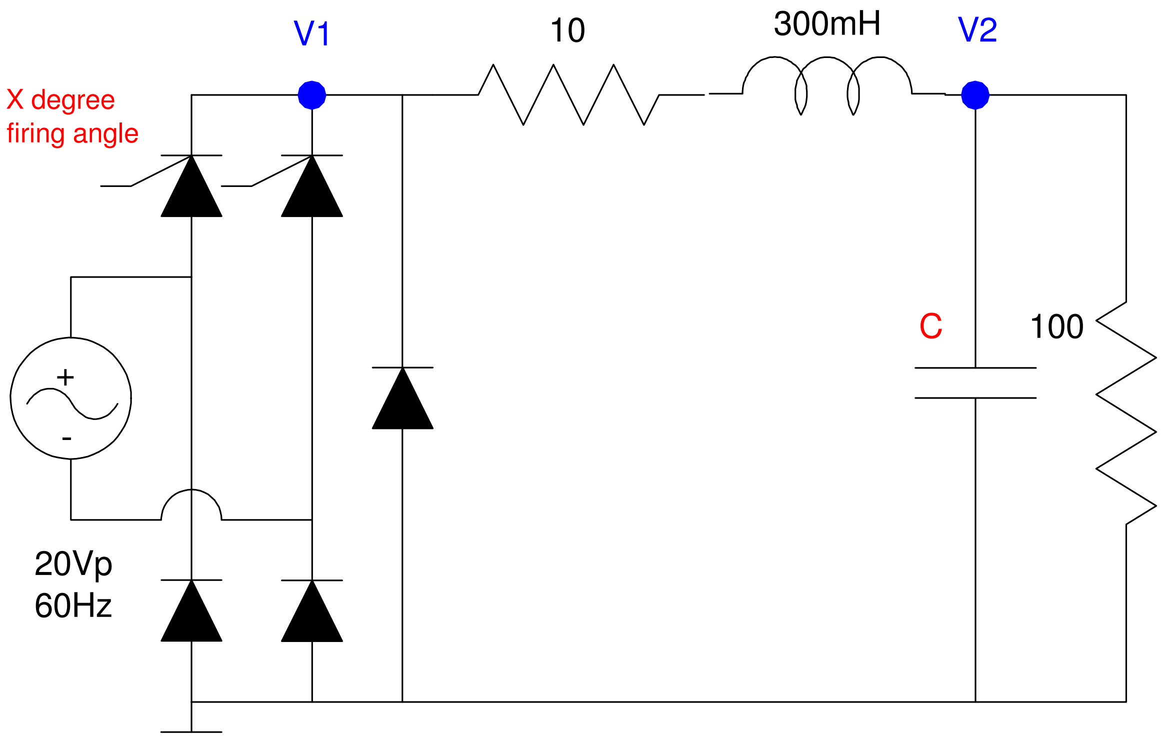


SCR: Design

- Input: 20Vp, 60Hz
- Output: 5VDC, 100 Ohms, 1Vpp ripple

Firing angle sets the DC voltage

L & C set the ripple (AC voltage)



SCR Design: DC

- Find the firing angle

$$V_2(DC) = 5.00V$$

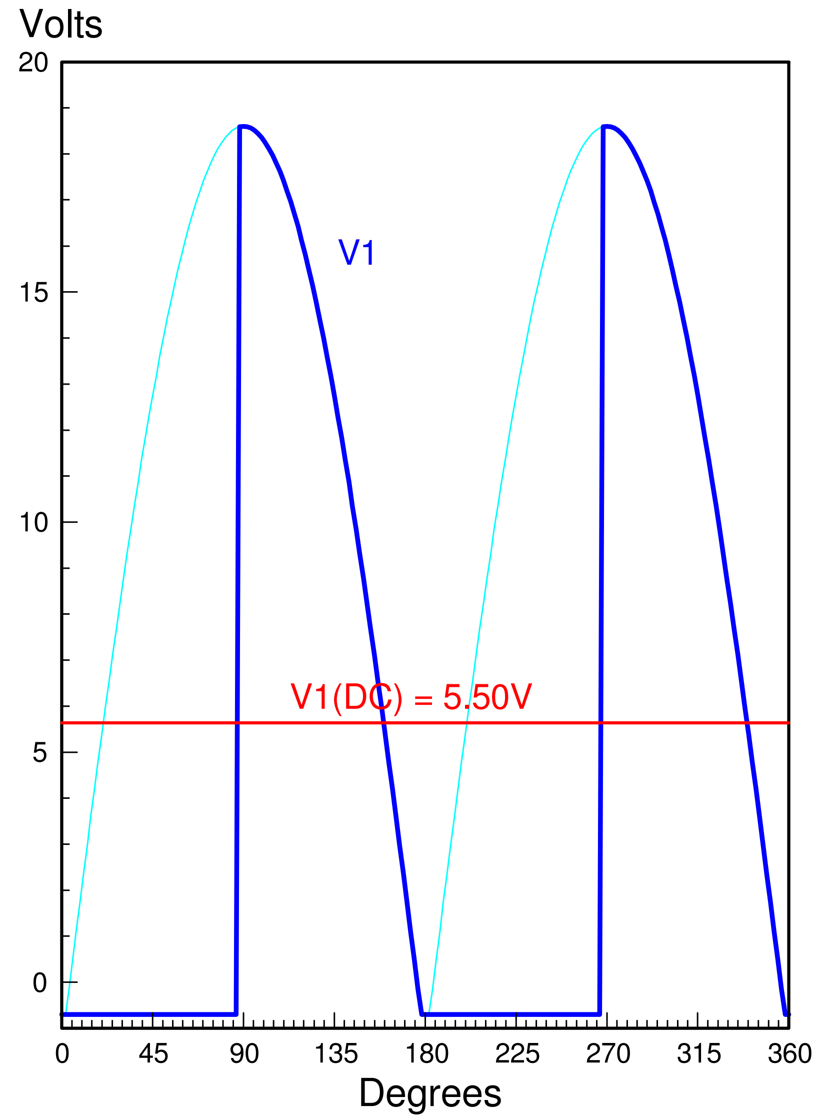
$$V_1(DC) = \left(\frac{100+10}{100}\right) V_2(DC)$$

$$V_1(DC) = 5.50V$$

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

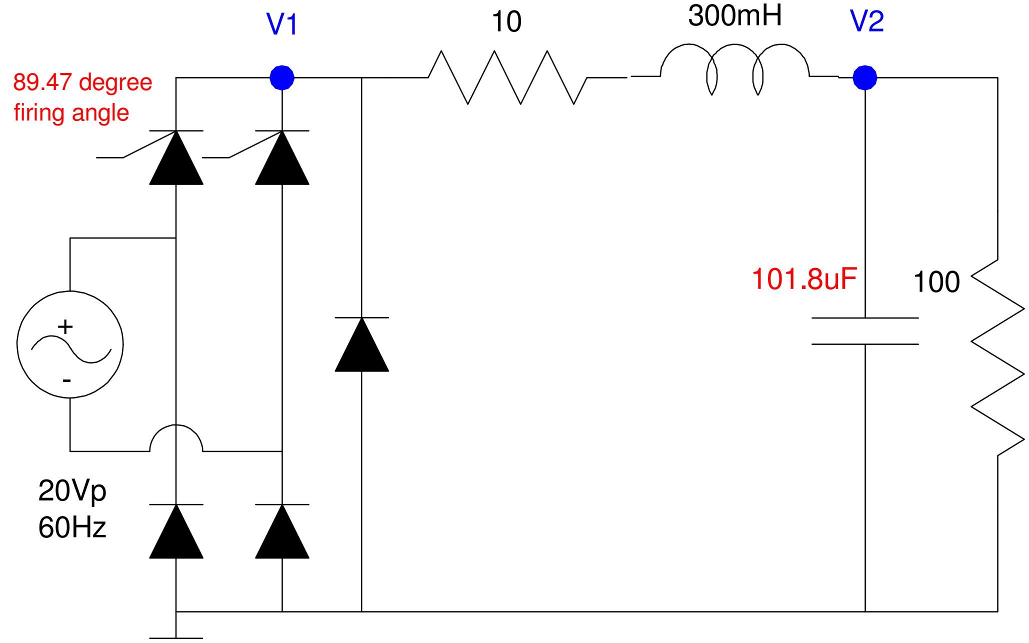
$$5.5V = \frac{19.3}{\pi} \cdot (1+\cos(\theta)) - 0.7$$

$$\theta = 89.47^0$$



SCR Design: AC

- Find C so that V2(AC) = 1Vpp
- The ripple at V1 is 19.3Vpp:
  - Fourier term would be more accurate



If C = 0, the ripple at V2 is

$$V_2 = \left(\frac{100}{(100)+(10+j226.2)}\right) \cdot 19.3V_{pp}$$

$$V_2 = 7.673V_{pp}$$

Pick C to reduce this ripple down to 1Vpp.

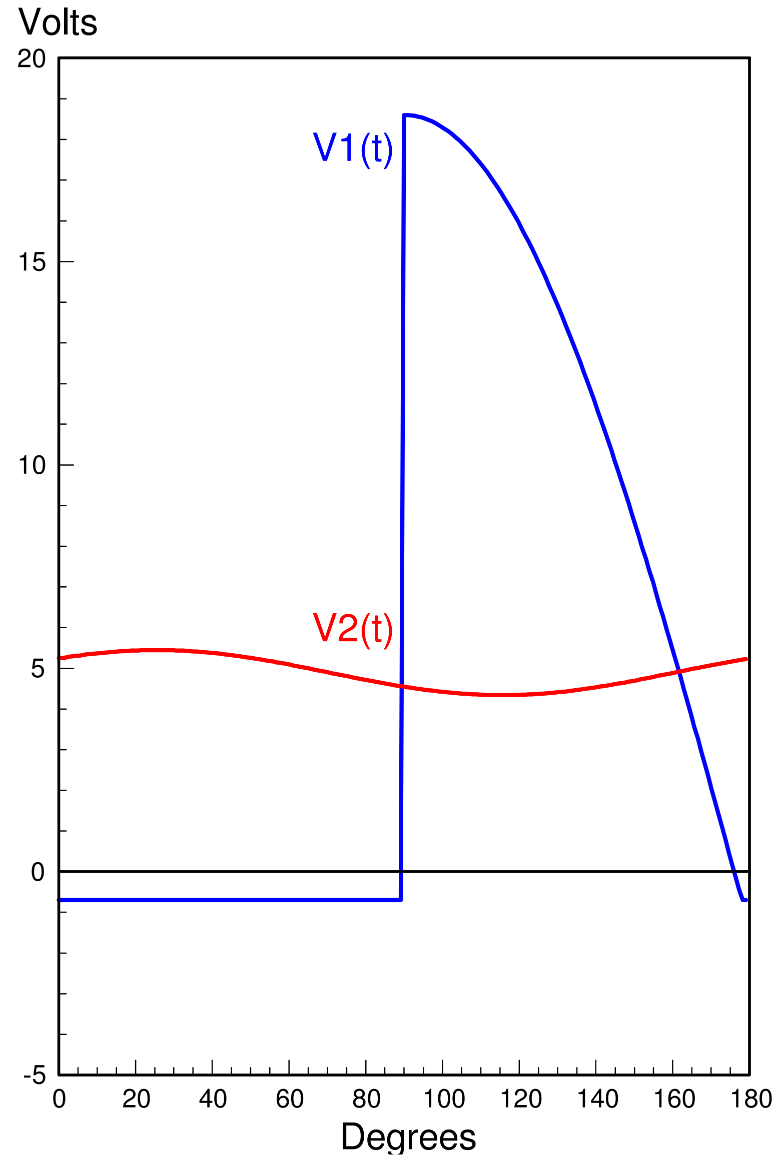
- Make C 7.673 times smaller than R

$$\frac{1}{\omega C} = \frac{1V_{pp}}{7.673V_{pp}} \cdot 100\Omega = 13.033\Omega$$

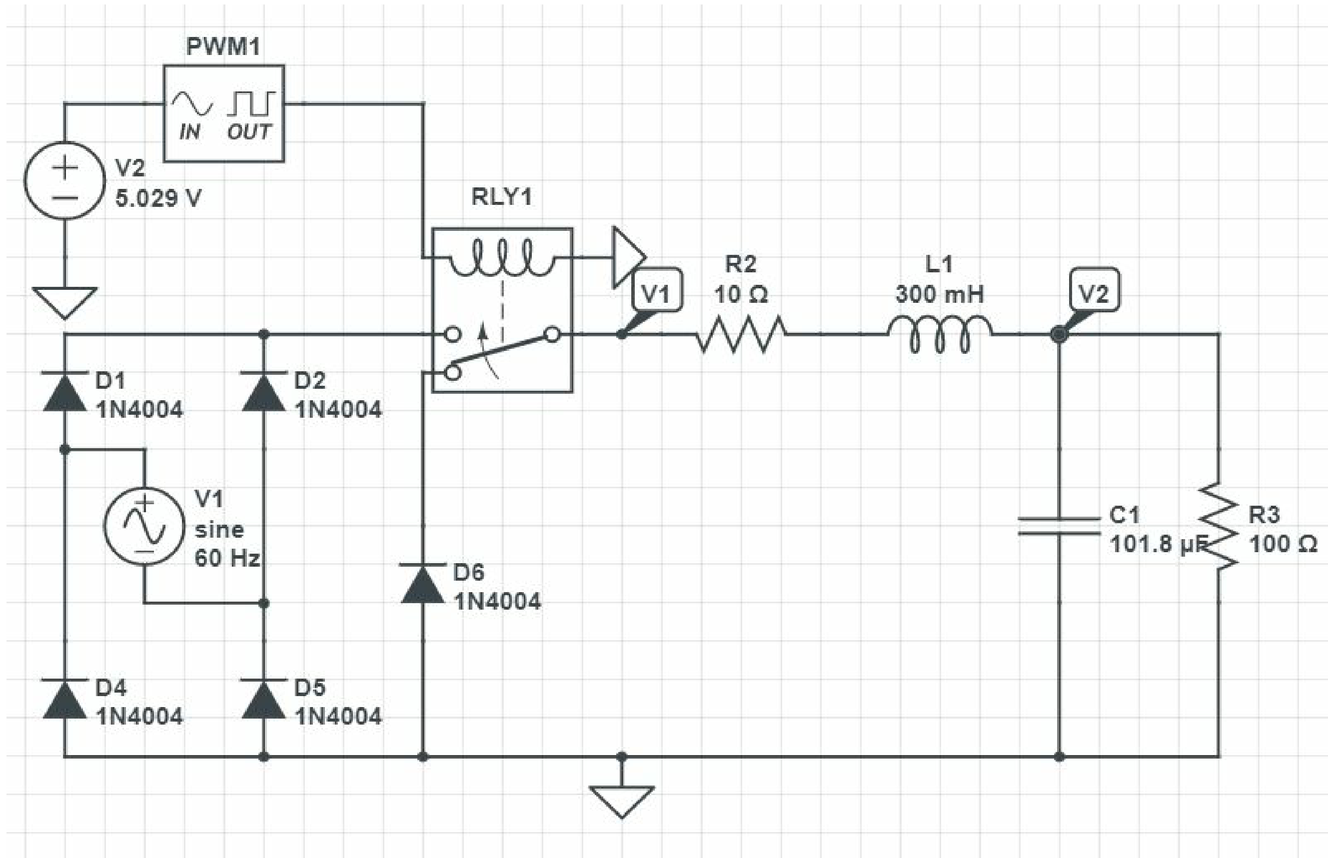
$$C = 101.8\mu F$$

Checking in Matlab

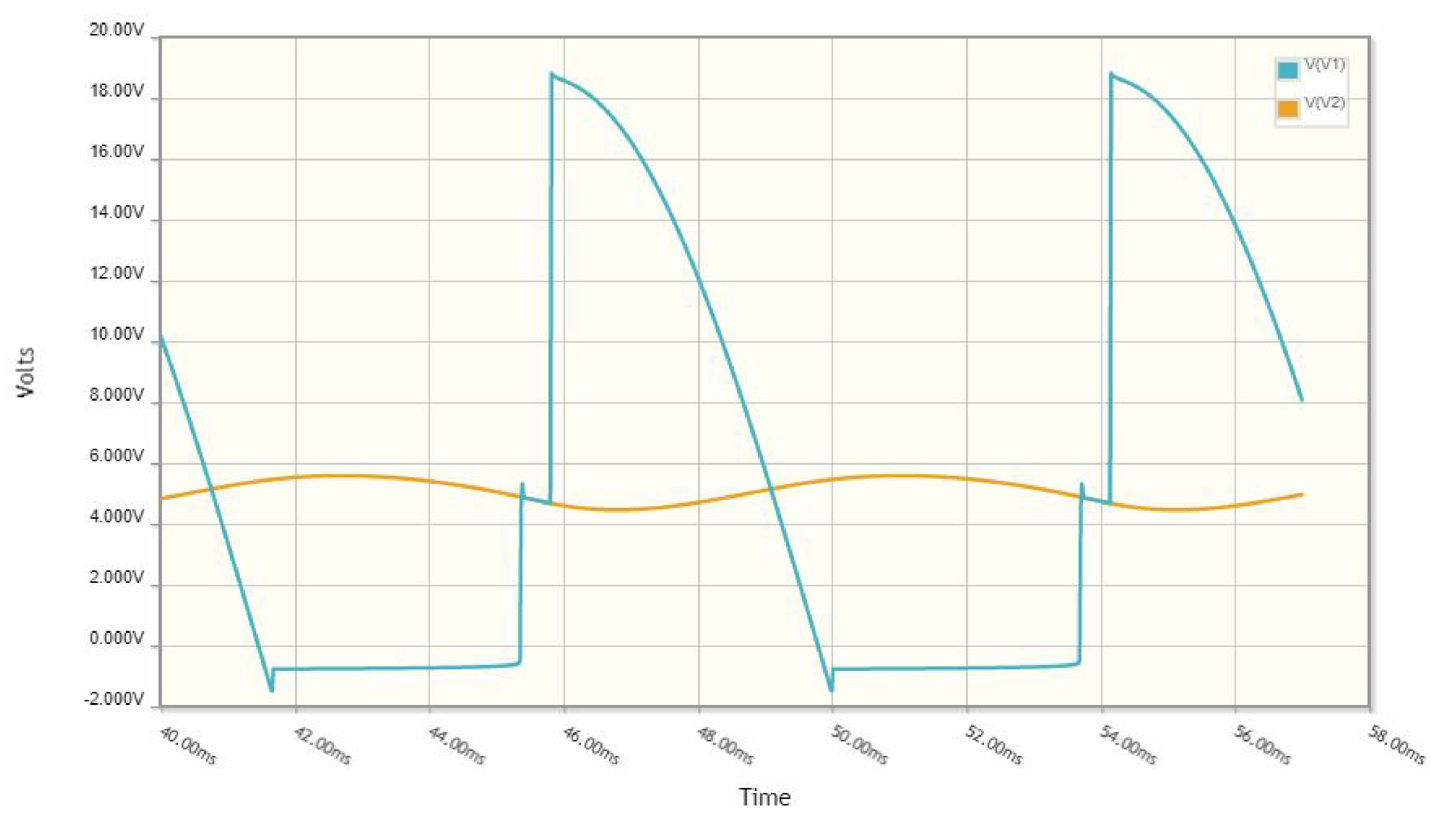
```
t = [0:0.001:1]';
V1 = max(-0.7,  20*sin(pi*t) - 1.4);
N = round(89.47/180 * 1000);
V1(1:N) = -0.7;

V1DC = mean(V1);
V2DC = (100/110)*V1DC

w = 2*pi*120;
R1 = 1 ./ (1/100 + j*w*101.8e-6);
R2 = 10 + j*w*0.3;

V1ac = 2*mean(V1 .* exp(-j*2*pi*t));
V1pp = 2*abs(V1ac);

V2ac = ( R1 / (R1 + R2) ) * V1ac;
V2pp = 2*abs(V2ac)
V2 = V2DC + real(V2ac) * cos(2*pi*t)
          - imag(V2ac) * sin(2*pi*t);

plot(t*180,V1,'b',t*180,V2,'r')
xlabel('degrees');
ylabel('Volts');


V2DC =    4.8923
V2pp =    1.1056
```



CircuitLab Simulation



- max(V2) = 5.580V
- min(V2) = 4.460V
- V2(DC) = (max + min)/2 = 5.02V (5.00V design)
- V2(AC) = (max - min) = 1.12Vpp (1.00Vpp design)



AC to DC Converter (take 3)

- Remove the 5th diode

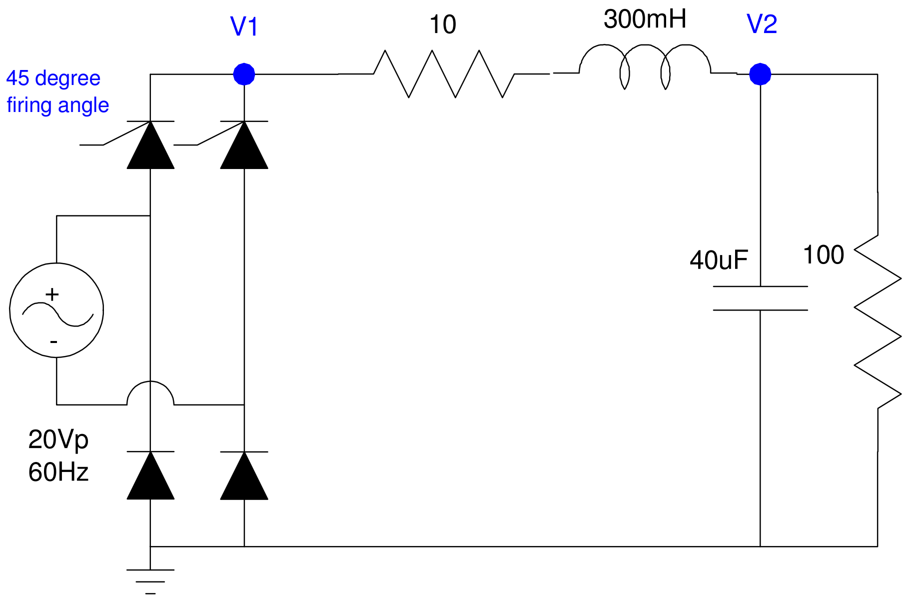
Changes

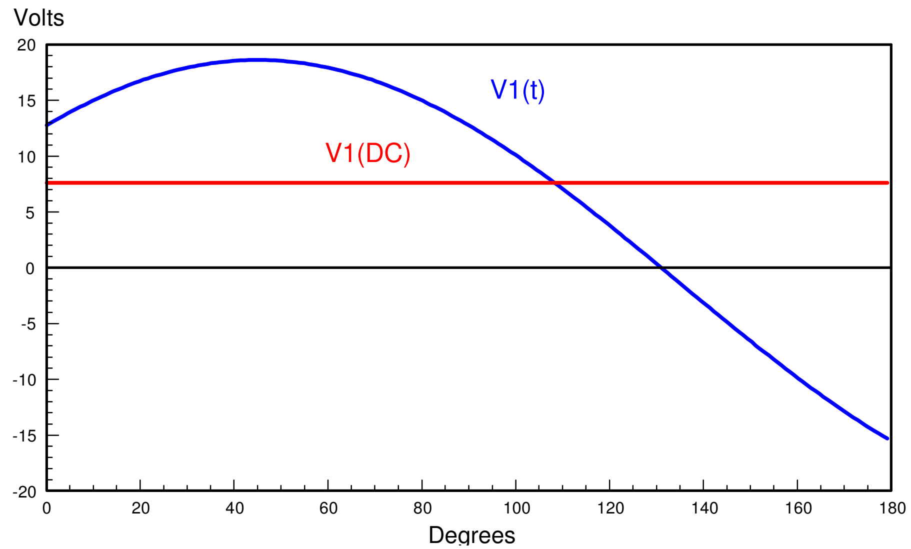
$$V_1 = \max(A, B, 0V)$$

to

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

This results in V1 going negative





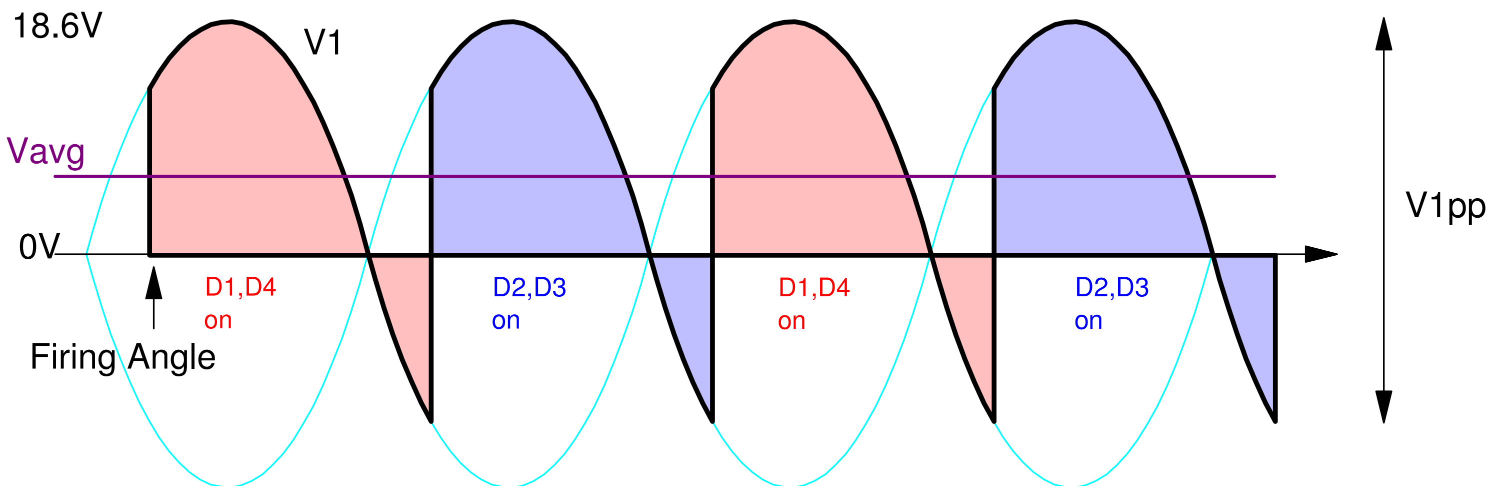
DC & AC Voltage at V1:

$$V_{avg} = \frac{1}{\pi} \cdot \int_{\theta}^{\pi+\theta} (V_p \sin(t) - 1.4)dt$$

$$V_{avg} = \frac{1}{\pi} \cdot V_p \cdot (\cos(t))_{\theta}^{\pi+\theta} - 1.4$$

$$V_{avg} = \frac{2}{\pi} \cdot V_p \cdot \cos(\theta) - 1.4$$

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



AC to DC Design Example (take 2):

Find the firing angle and C so that V2 is

- 10VDC
- 1Vpp ripple

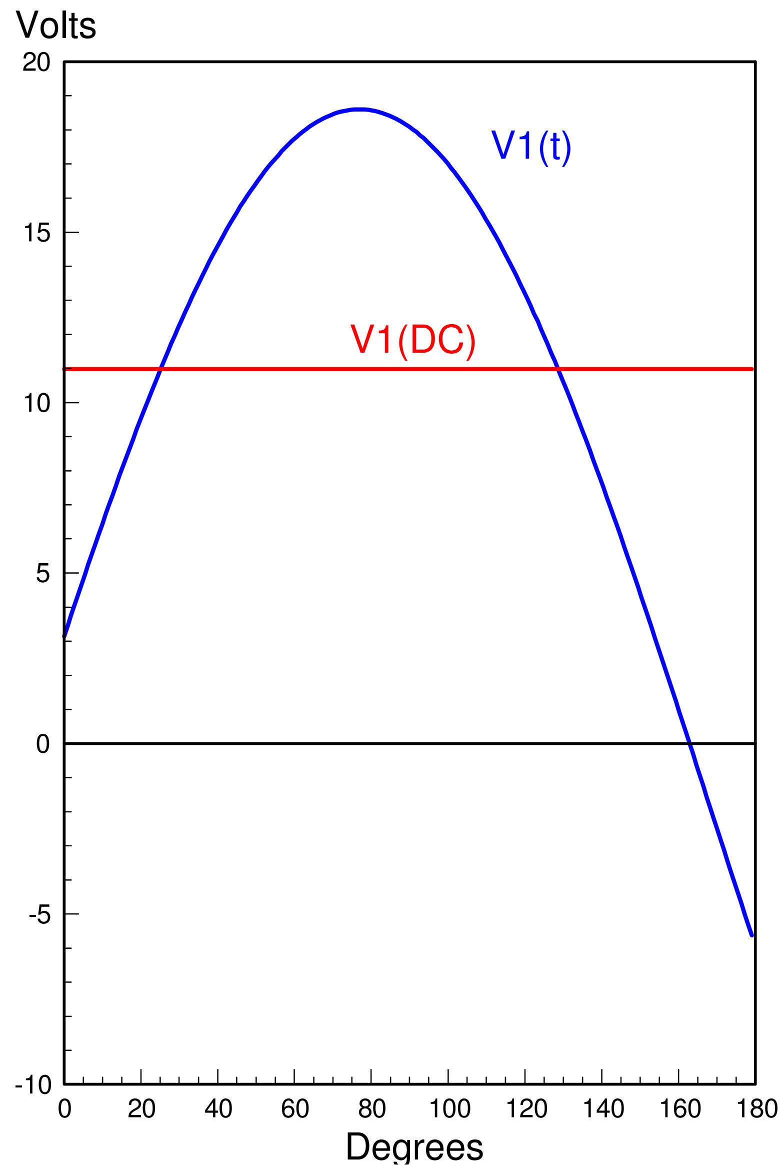
For V2(DC) = 10V

$$V_1(DC) = \left(\frac{110}{100}\right) V_2(DC) = 11.0V$$

$$V_1(DC) = \frac{2}{\pi} \cdot V_p \cdot \cos(\theta)$$

$$11V = \frac{2}{\pi} \cdot 20.0 \cdot \cos(\theta) - 1.4$$

$$\theta = 13.121^0$$



AC Analysis (L & C)

$$V_{1pp} = \max(V_1) - \min(V_1) = 18.6V - (-5.94V) = 24.54V_{pp}$$

Using the Fourier Tranform would be more accurate

If C = 0, the ripple at V2 is

$$V_2(AC) = \left(\frac{100}{100+(10+j226.2)}\right)24.54V_{pp}$$

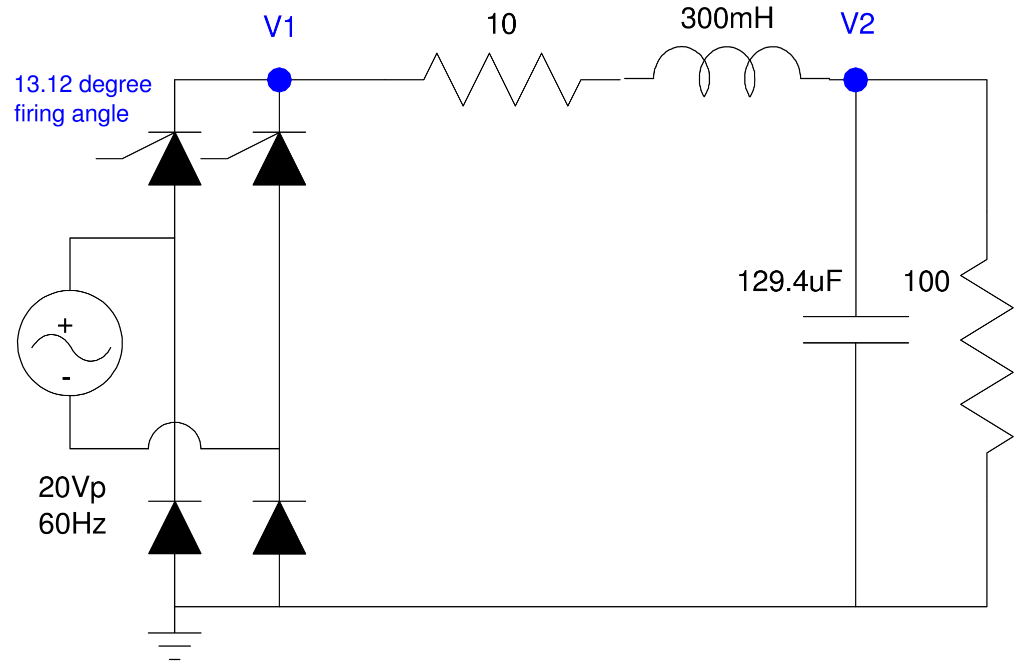
$$V_2(AC) = 9.756V_{pp}$$

C reduces R to set the ripple

$$\left|\frac{1}{j\omega C}\right| = \left(\frac{1V_{pp}}{9.756V_{pp}}\right)100\Omega$$

$$\left|\frac{1}{j\omega C}\right| = 10.25\Omega$$

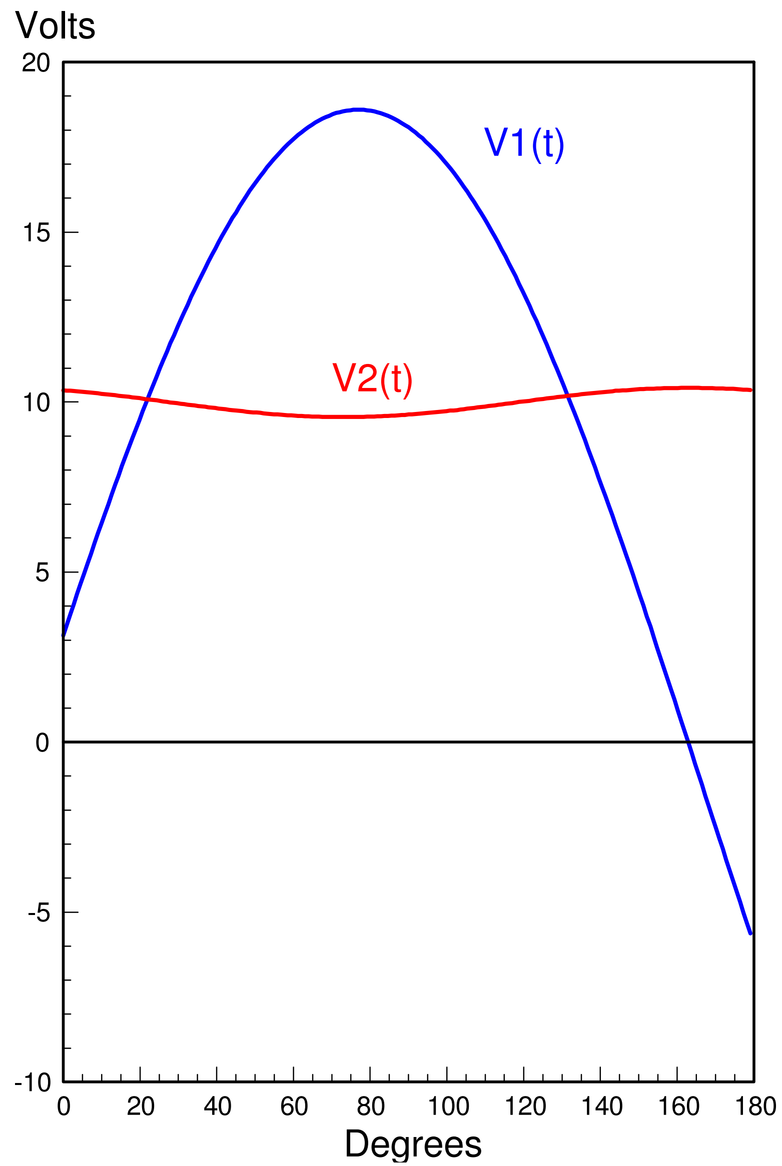
$$C = 129.4\mu F$$



Simulation Results

- V2(DC) = 9.9891V
- V2(AC) = 0.8591Vpp

```
t = [0:0.001:1]';
q = 13.121;      % firing angle
V1 = 20*sin(pi*t + q*pi/180) - 1.4;

V1DC = mean(V1);
V2DC = (100/110)*V1DC

w = 2*pi*120;
C = 129.4e-6;
L = 0.3;
R1 = 1 ./ (1/100 + j*w*C);
R2 = 10 + j*w*L;

V1ac = 2*mean(V1 .* exp(-j*2*pi*t));
V1pp = 2*abs(V1ac);

V2ac = ( R1 / (R1 + R2) ) * V1ac;
V2pp = 2*abs(V2ac)
V2 = V2DC + real(V2ac) * cos(2*pi*t)
          - imag(V2ac) * sin(2*pi*t);

plot(t*180,V1,'b',t*180,V2,'r')
xlabel('degrees');
ylabel('Volts');
```



Summary

SCR's allow you to convert AC to DC

- The firing angle lest you adjust the DC voltage
- L and C let you adjust the ripple

Approximating the AC voltage at V1 as

V1(AC) = max(V1) - min(V1)

gets you close.

Using the first 2-terms of the Fourier Transform (DC + 120Hz) is better

- but harder without Matlab