
Semiconductor Relays (SCR)

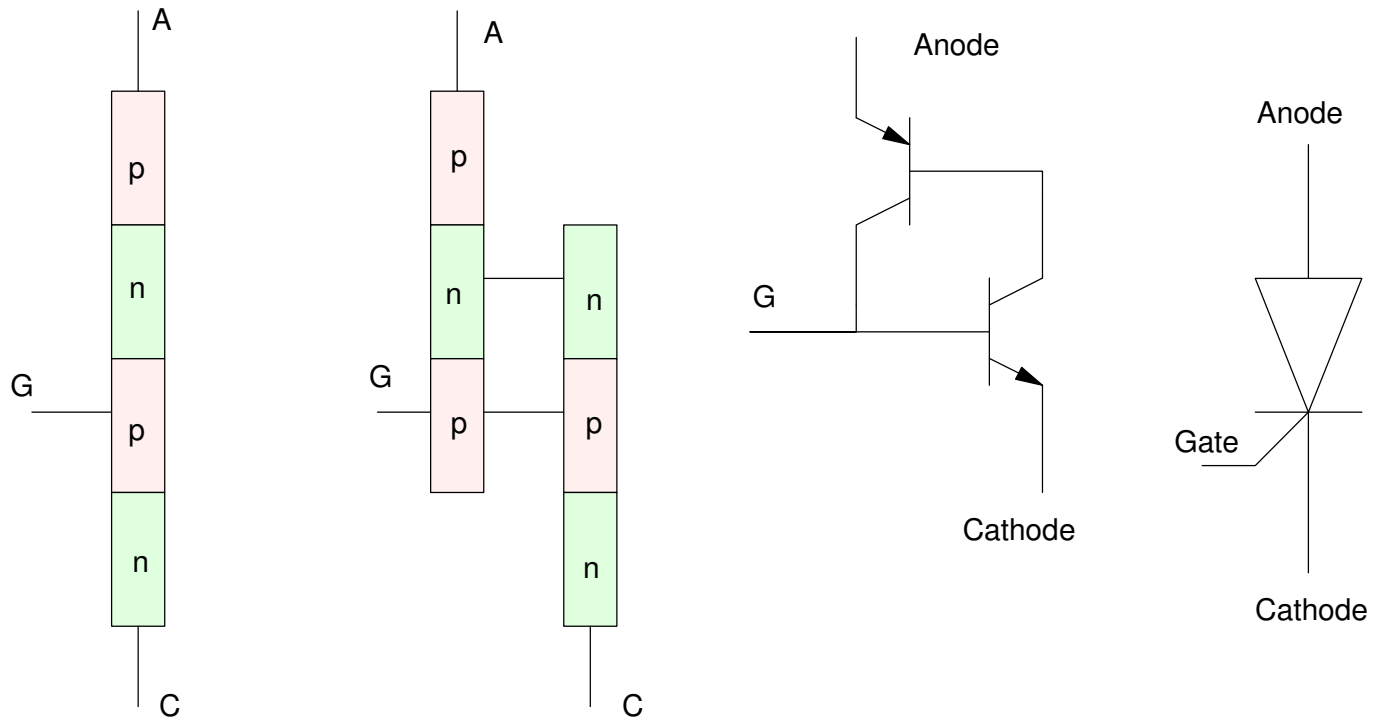
ECE 320 Electronics I

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 $+V_a$ and the cathode is $0V$.

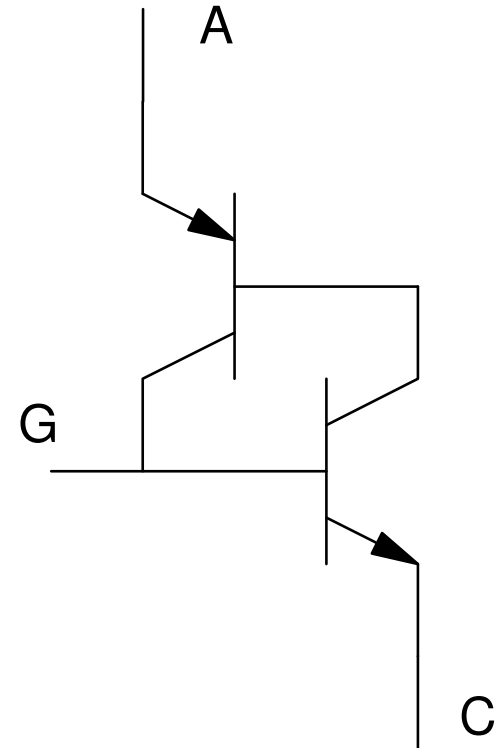
- Off: $I_b = 0$
- Once off, it remains off

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

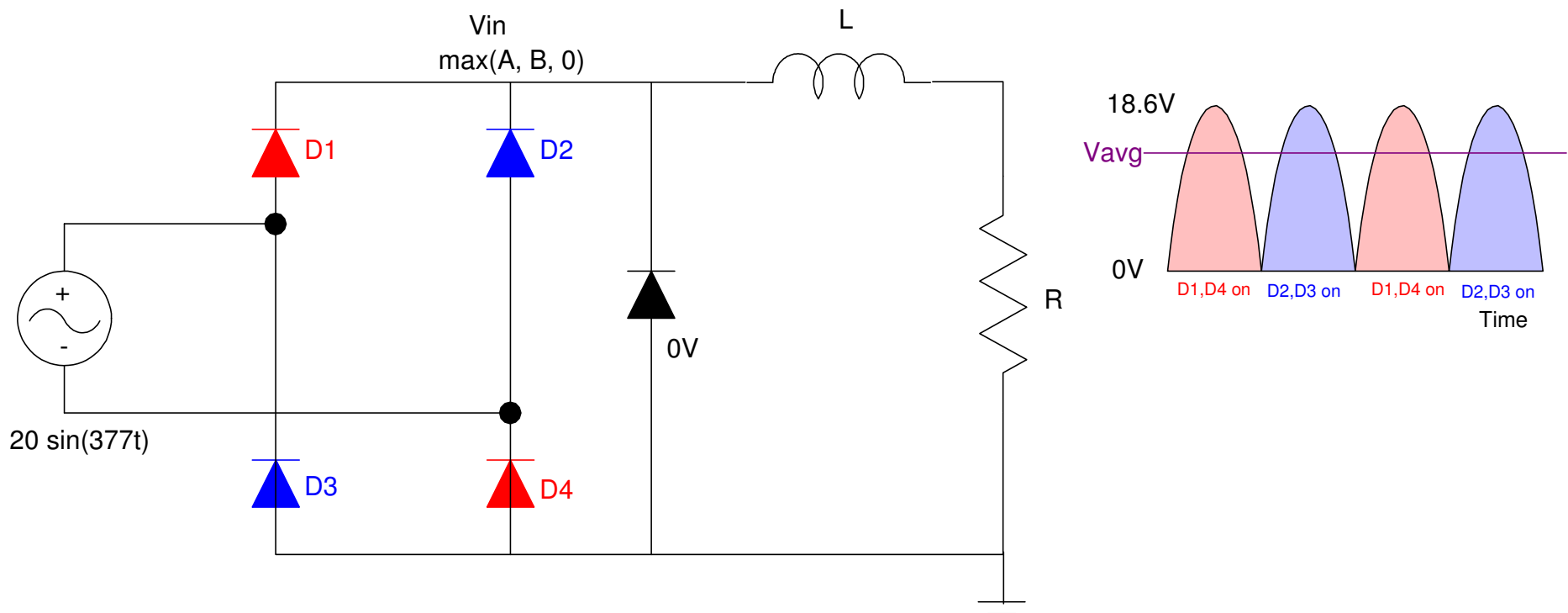
- I_g turns it on



AC to DC Converter:

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

- Firing Angle = 0 degrees
- $V_{avg} = 0.6366 V_p$

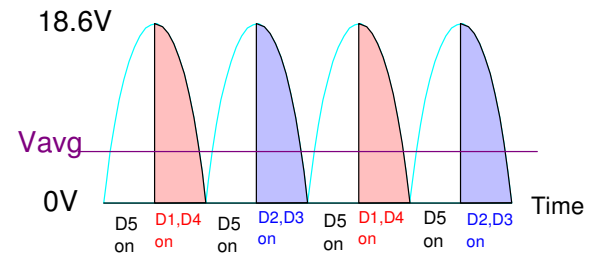
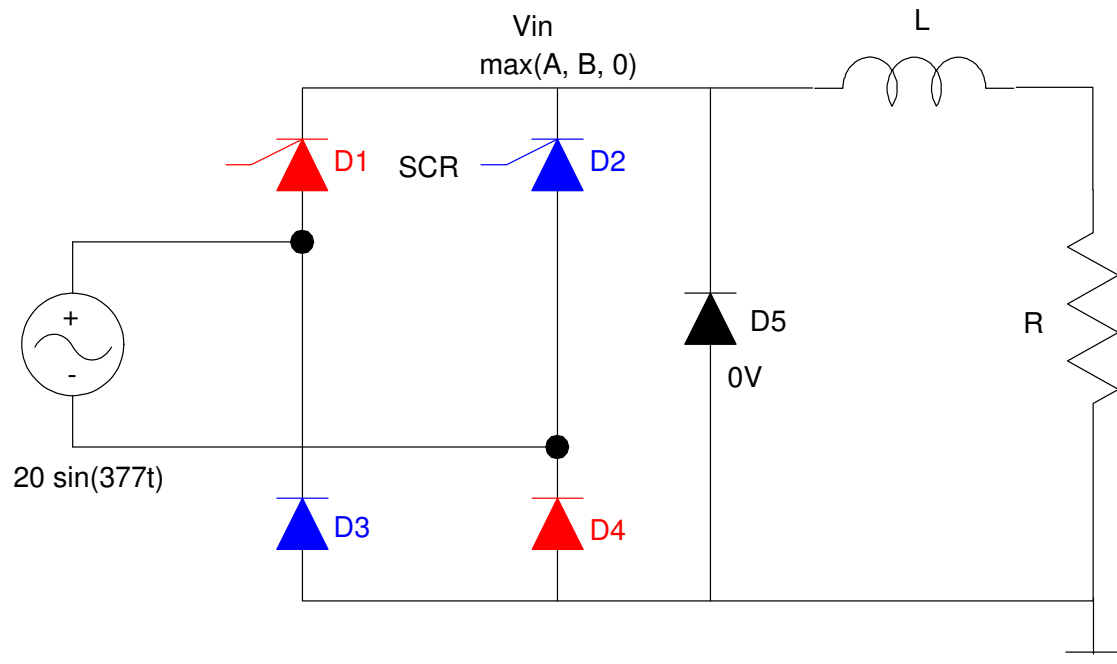


Four diodes creating a full-wave rectifier. A 5th diode is added for the SCR (coming soon...)

Firing Angle = θ

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

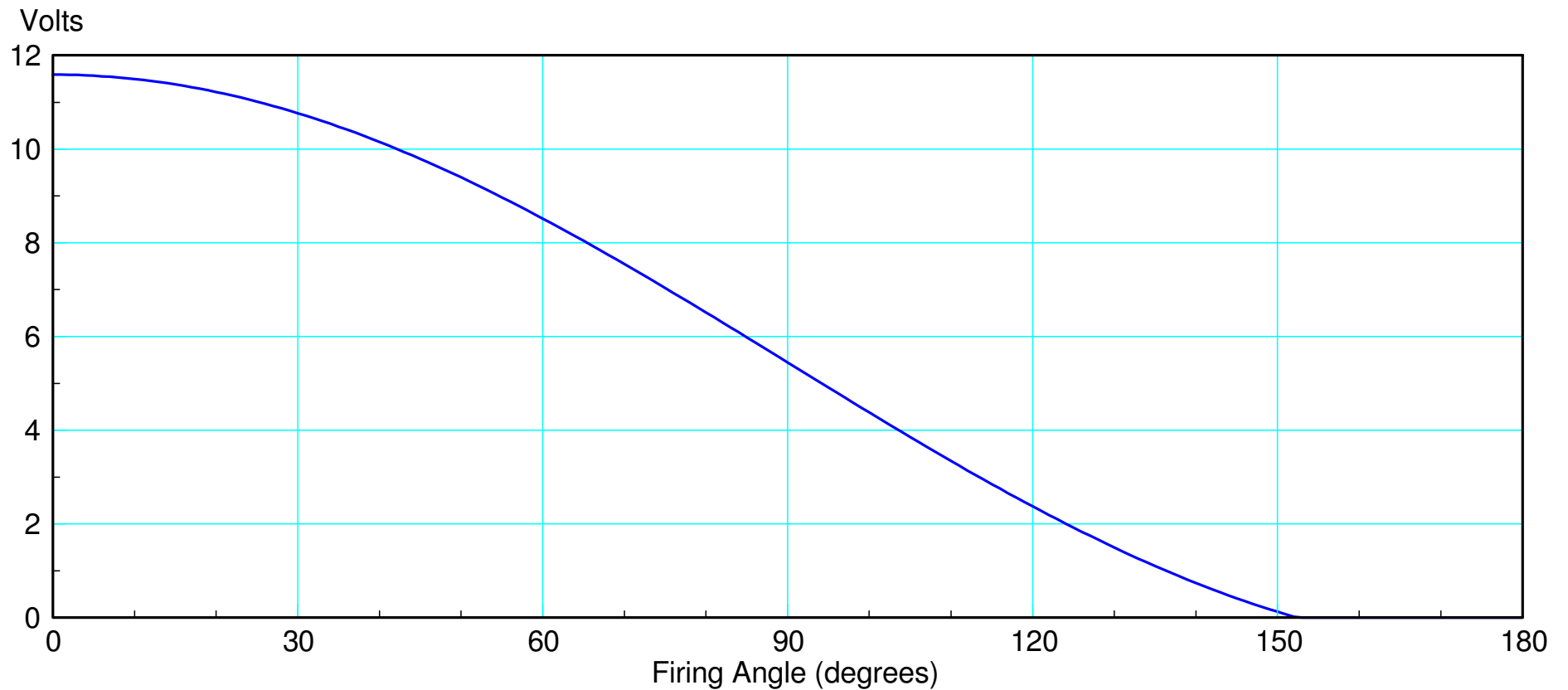
$$V_{avg} \approx \left(\frac{V_p - 0.7}{\pi} \right) \cdot (1 + \cos(\theta)) - 0.7$$



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

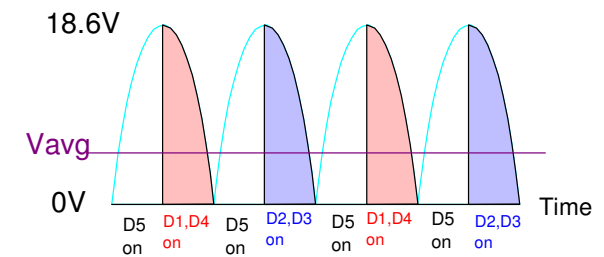
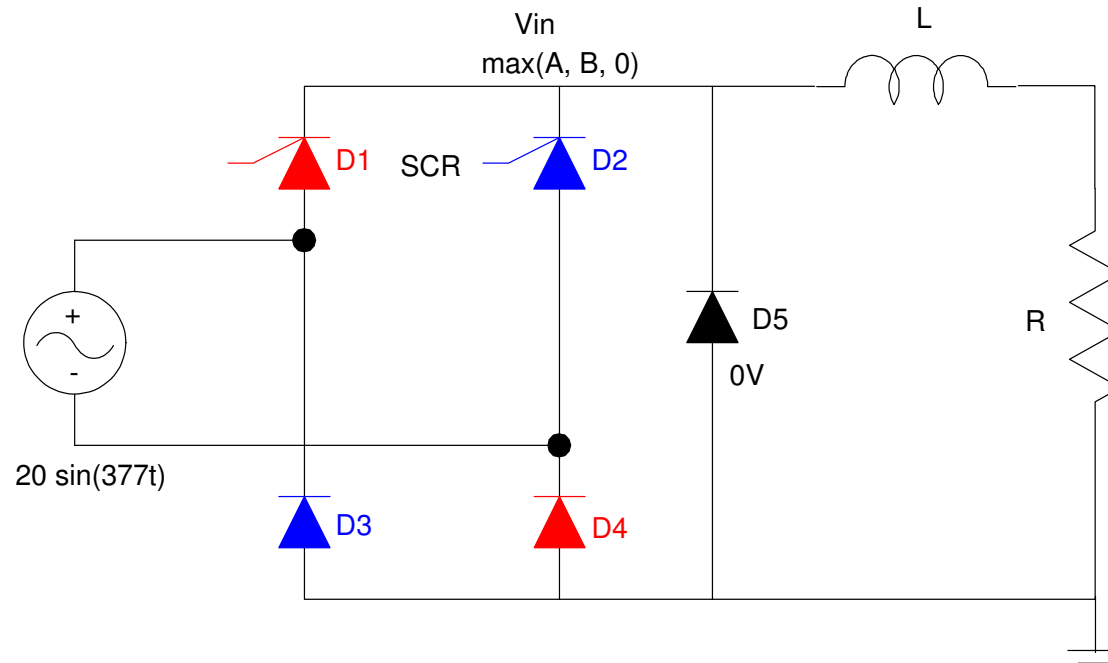
Firing Angle vs. Voltage

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



Resolution:

- 180 degrees = 8.333ms (60Hz)
- 1 clock = 100ns (PIC18F4620)
- Able to control the DC voltage 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

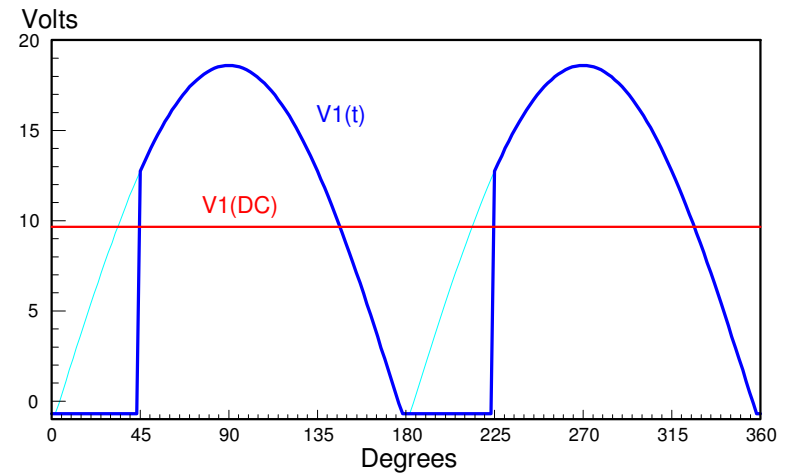
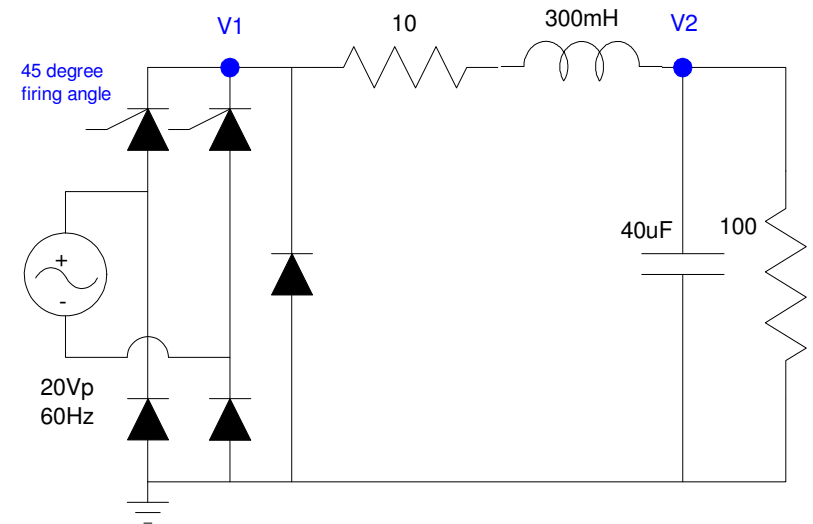
DC Analysis

$$V_1(DC) = \left(\frac{19.3V}{\pi} \right) \cdot (1 + \cos(45^\circ)) - 0.7$$

$$V_1(DC) = 9.787V$$

$$V_2(DC) = \left(\frac{100}{100+10} \right) \cdot 9.797$$

$$V_2(DC) = 8.898V$$



AC Analysis (take 1)

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

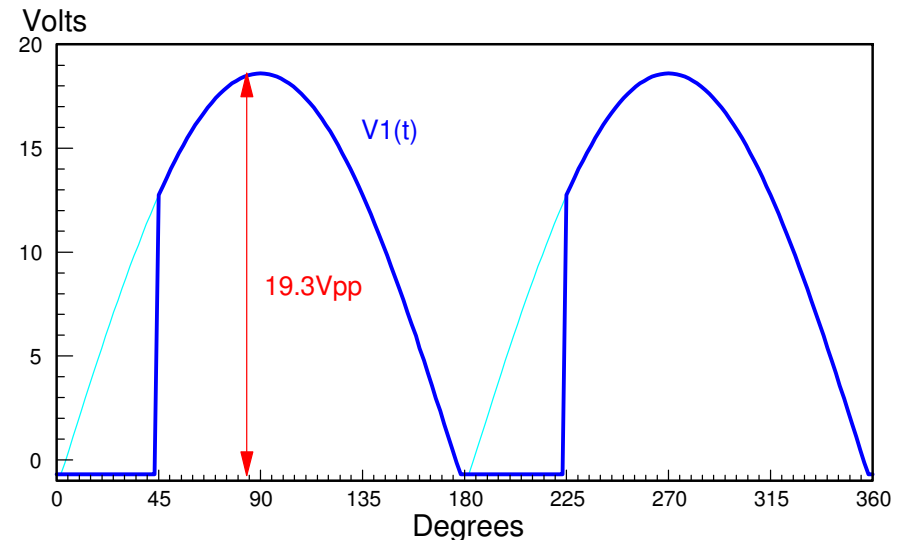
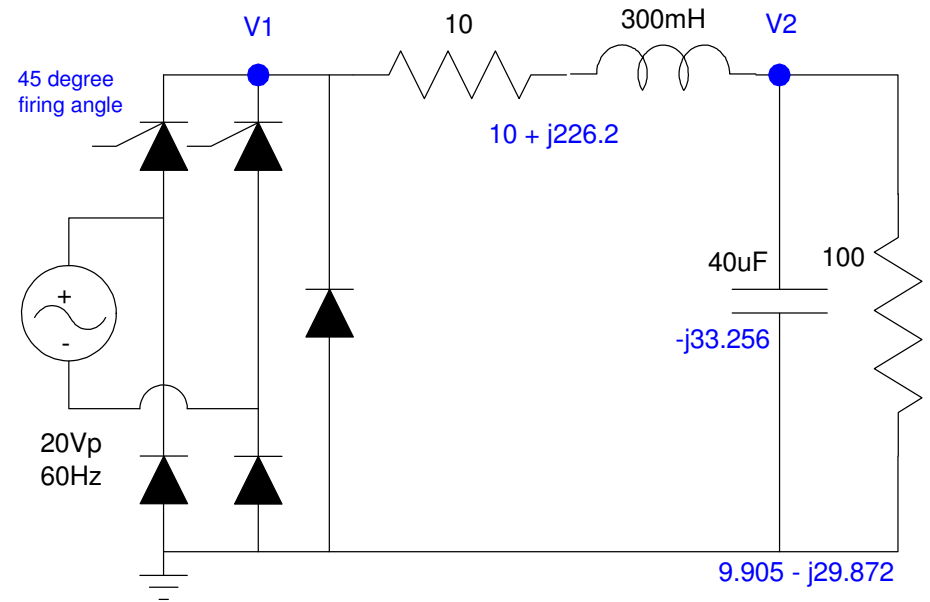
$$V_1(AC) \approx 19.3V_{pp}$$

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

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

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 transform

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

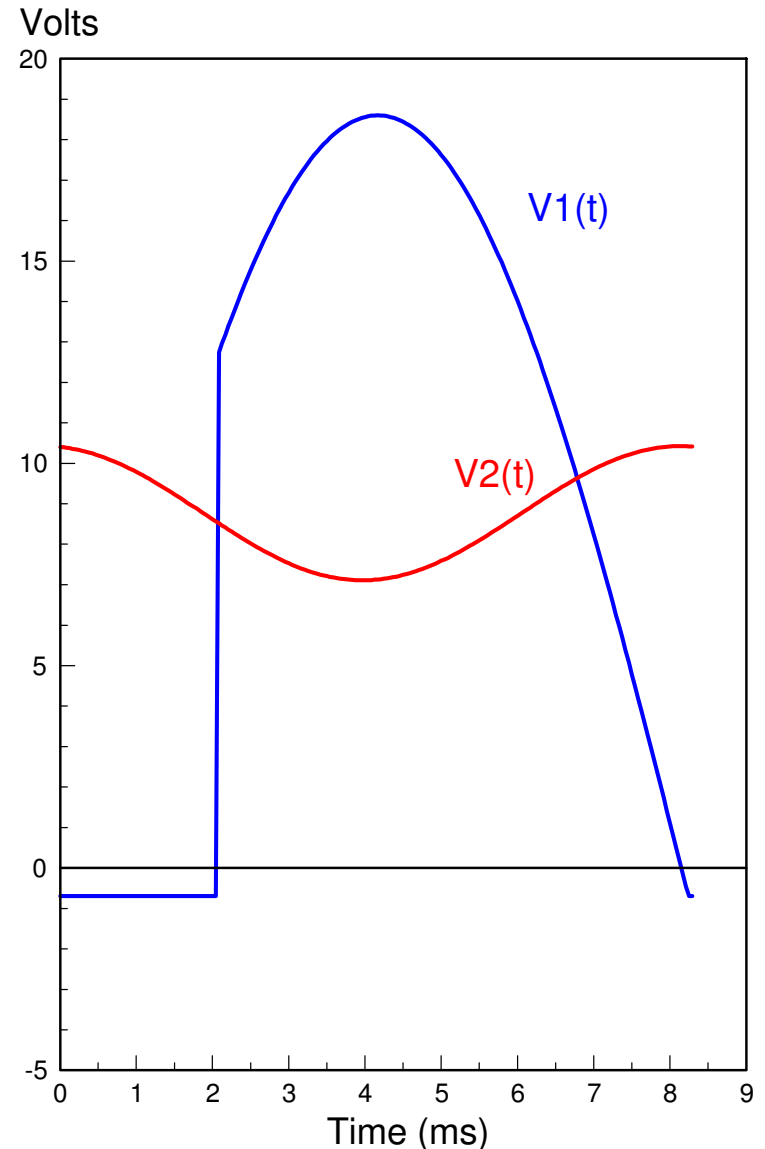
```
t = [0:0.001:1]';  
V1 = max(-0.7, 20*sin(pi*t) - 1.4);  
V1(1:250) = -0.7; % 45 degrees
```

```
V1DC = mean(V1)  
V1DC = 9.6431  
V2DC = (100/110)*V1DC  
V2DC = 8.7664
```

```
V1p = 2*mean(V1 .* exp(-j*2*pi*t));  
V1pp = 2*abs(V1p)  
v1pp = 20.7625 % vs. 19.3V
```

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

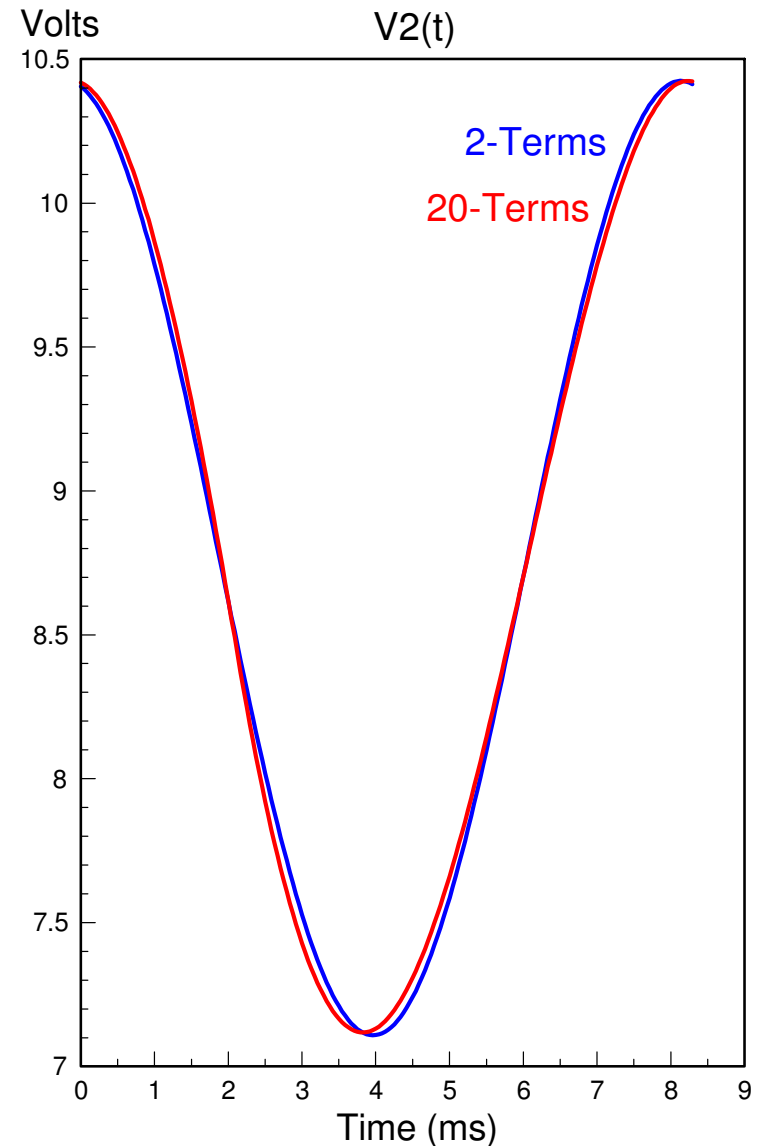
```
v2pp = 3.3161 % vs. 2.2365Vpp
```



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	3.3161 Vpp
Fourier 20-terms	8.7664 V	3.3059 Vpp
CircuitLab (coming soon)	8.898 V	3.292 Vpp

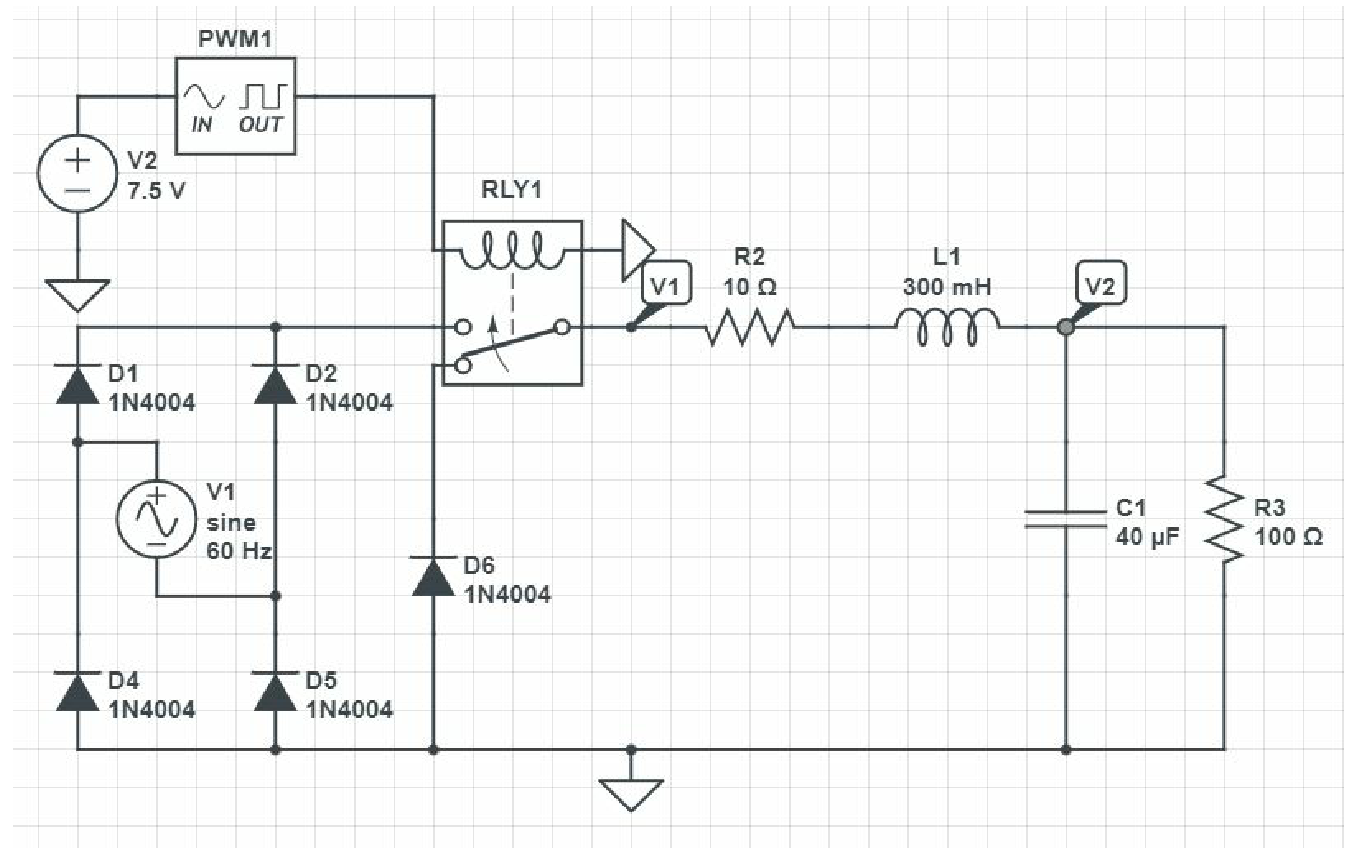


CircuitLab Simulation

SCR's are currently not working

Approximate it with

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



CircuitLab Simulation Result

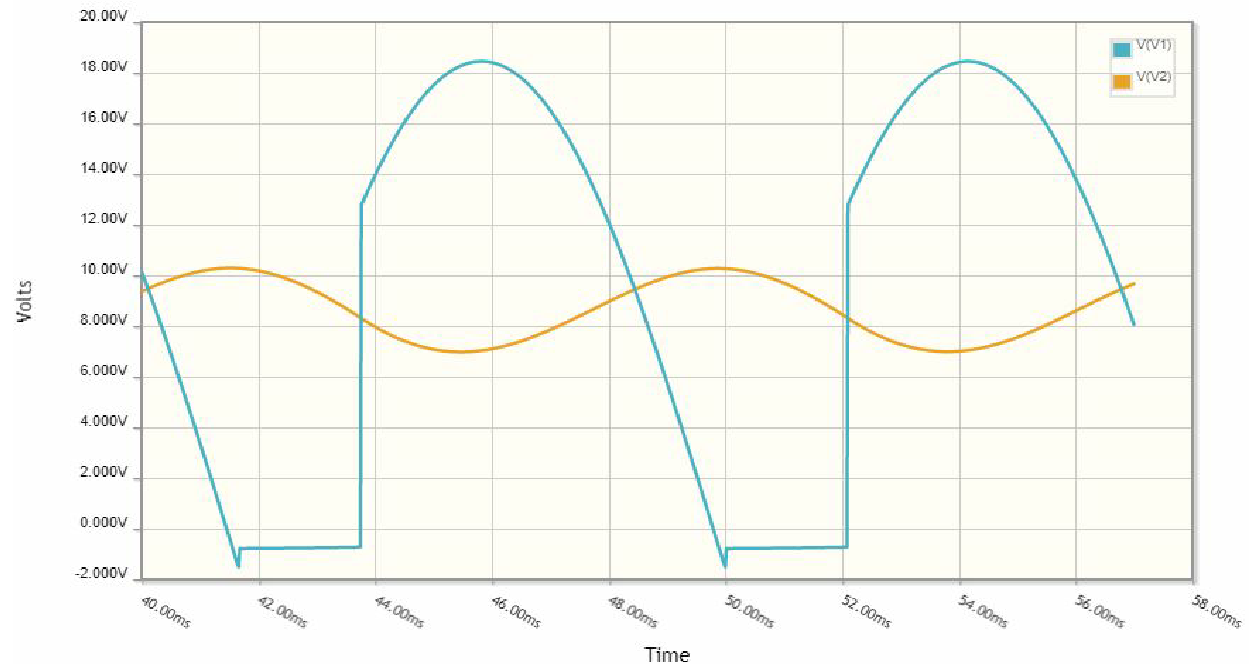
- V1 = blue
- V2 = orange
- $\max(V2) = 10.27V$
- $\min(V2) = 6.978V$

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

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

$$V2(AC) = (\max - \min)$$

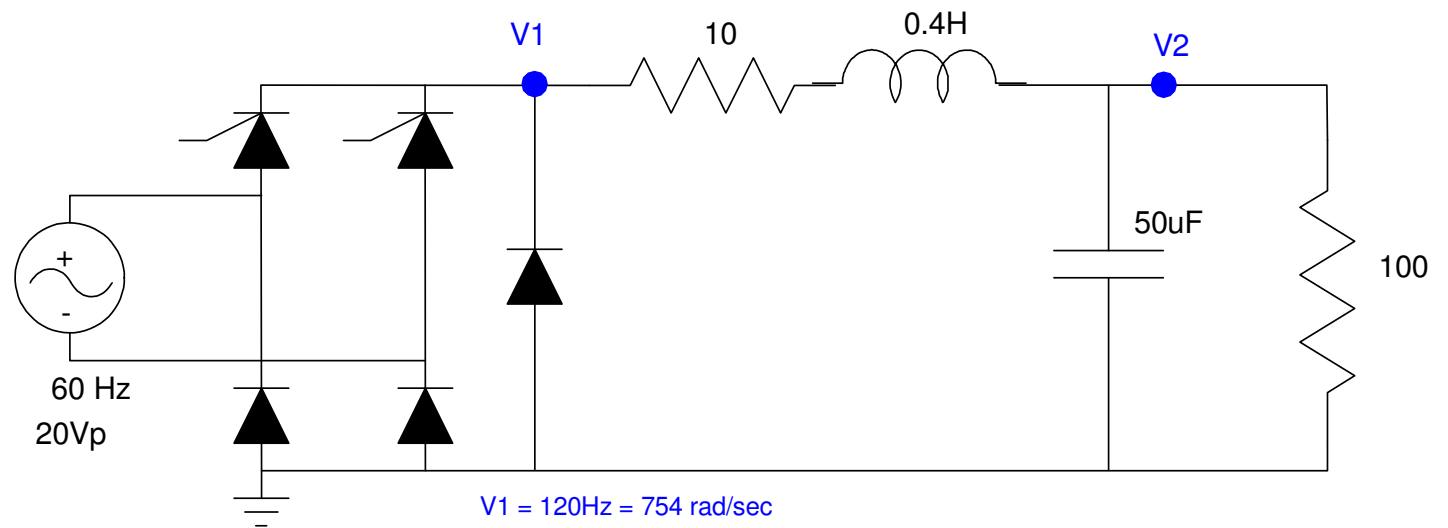
- $V2(AC) = 3.292V_{pp}$
- vs. $2.229V_{pp}$ calculated



Handout:

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

- Assume a firing angle of 25 degrees

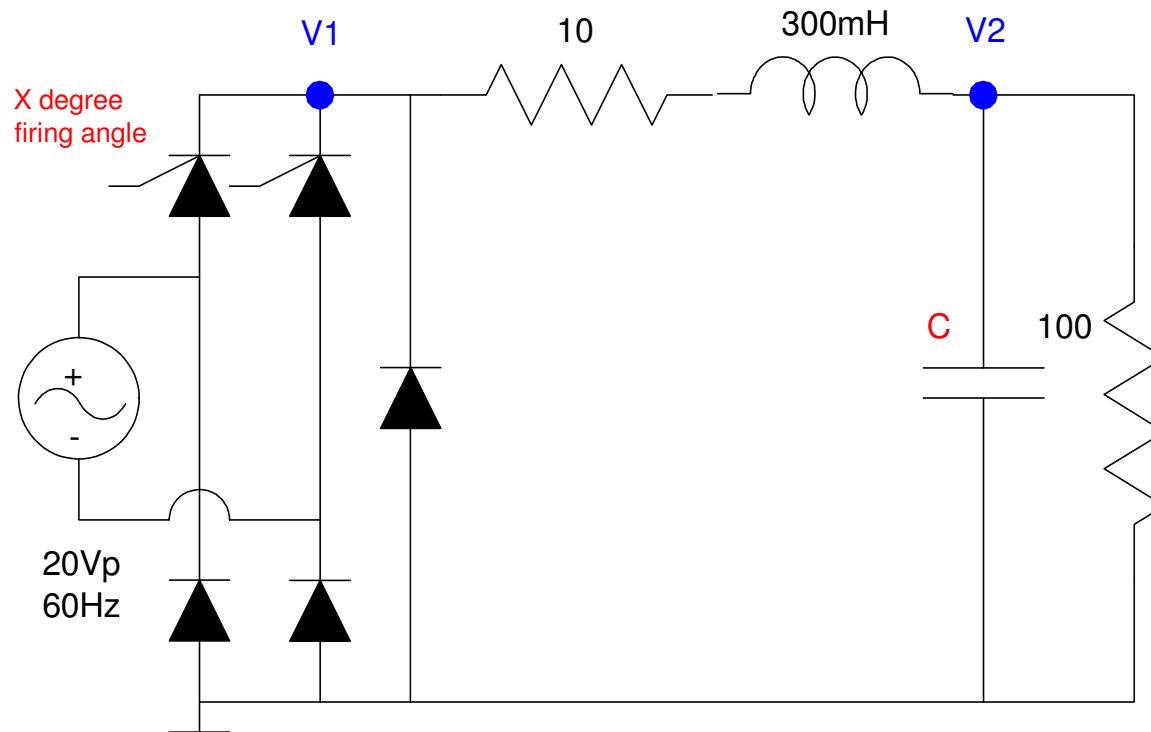


SCR: Design

- 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

$$V_2(DC) = 5.00V$$

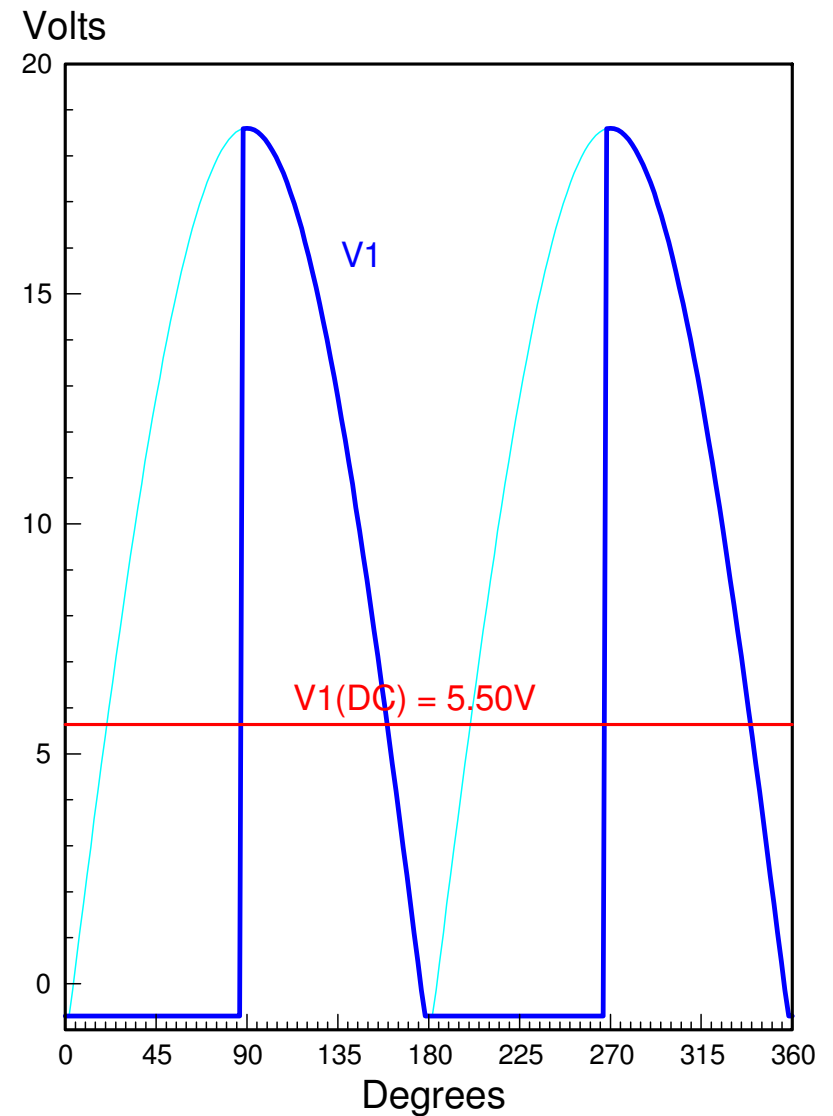
$$V_1(DC) = \left(\frac{100+10}{100} \right) V_2(DC)$$

$$V_1(DC) = 5.50V$$

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

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

$$\theta = 89.47^\circ$$



SCR Design: AC

- Find C so that $V_2(\text{AC}) = 1\text{V}_{pp}$
- The ripple at V1 is 19.3V_{pp} :
 - Fourier term would be more accurate

If $C = 0$, the ripple at V2 is

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

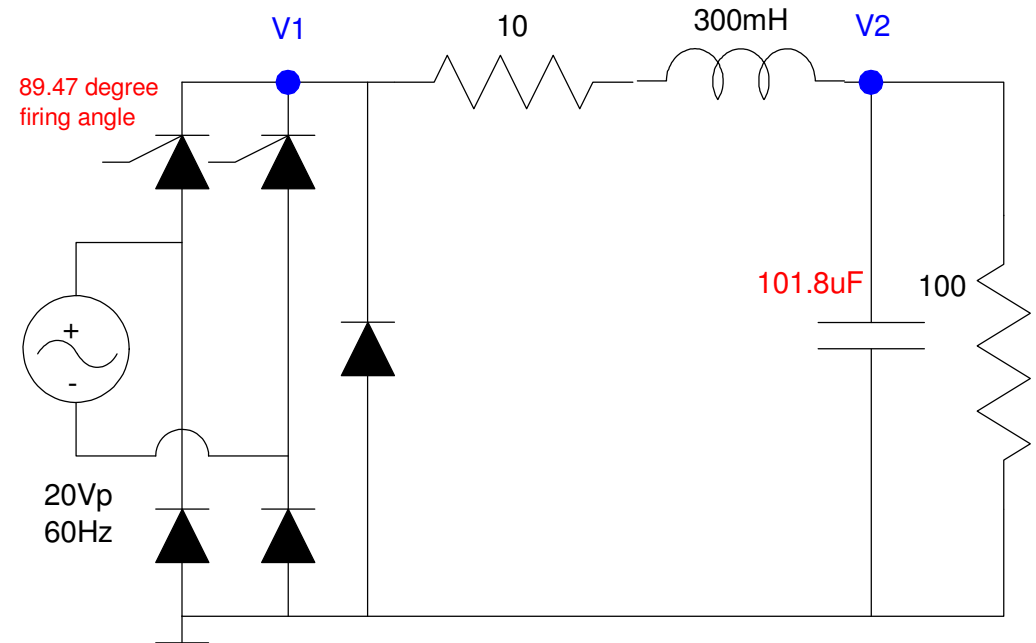
$$V_2 = 7.673\text{V}_{pp}$$

Pick C to reduce this ripple down to 1V_{pp} .

- Make C 7.673 times smaller than R

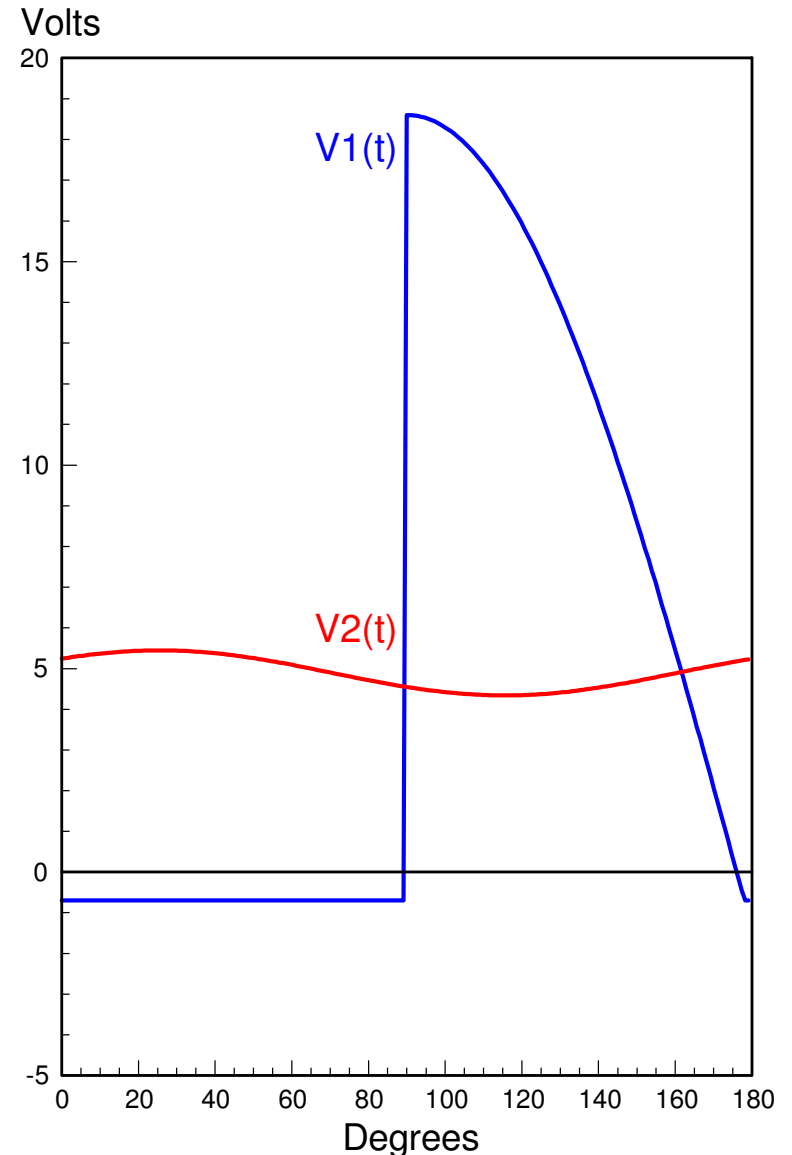
$$\frac{1}{\omega C} = \frac{1\text{V}_{pp}}{7.673\text{V}_{pp}} \cdot 100\Omega = 13.033\Omega$$

$$C = 101.8\mu\text{F}$$

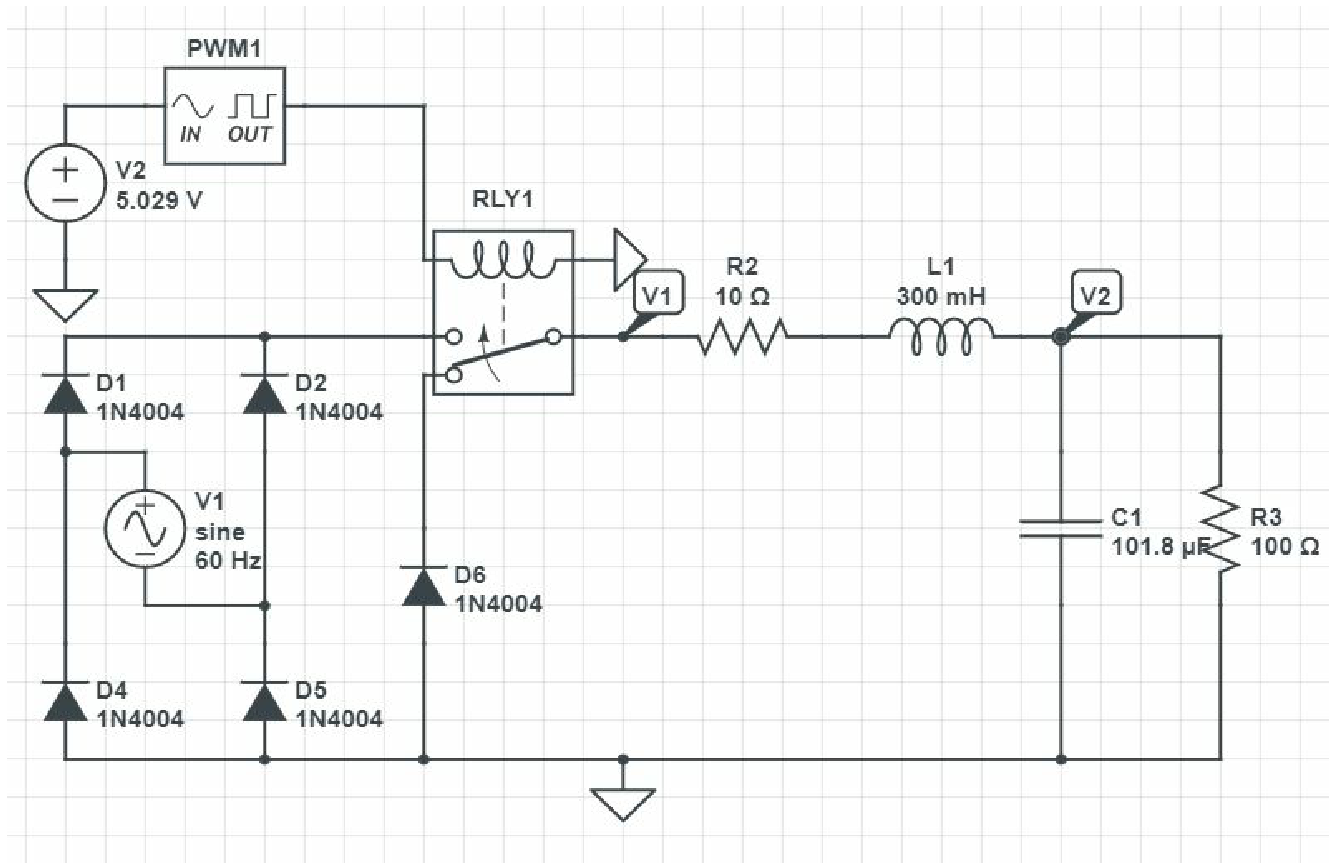


Checking in Matlab

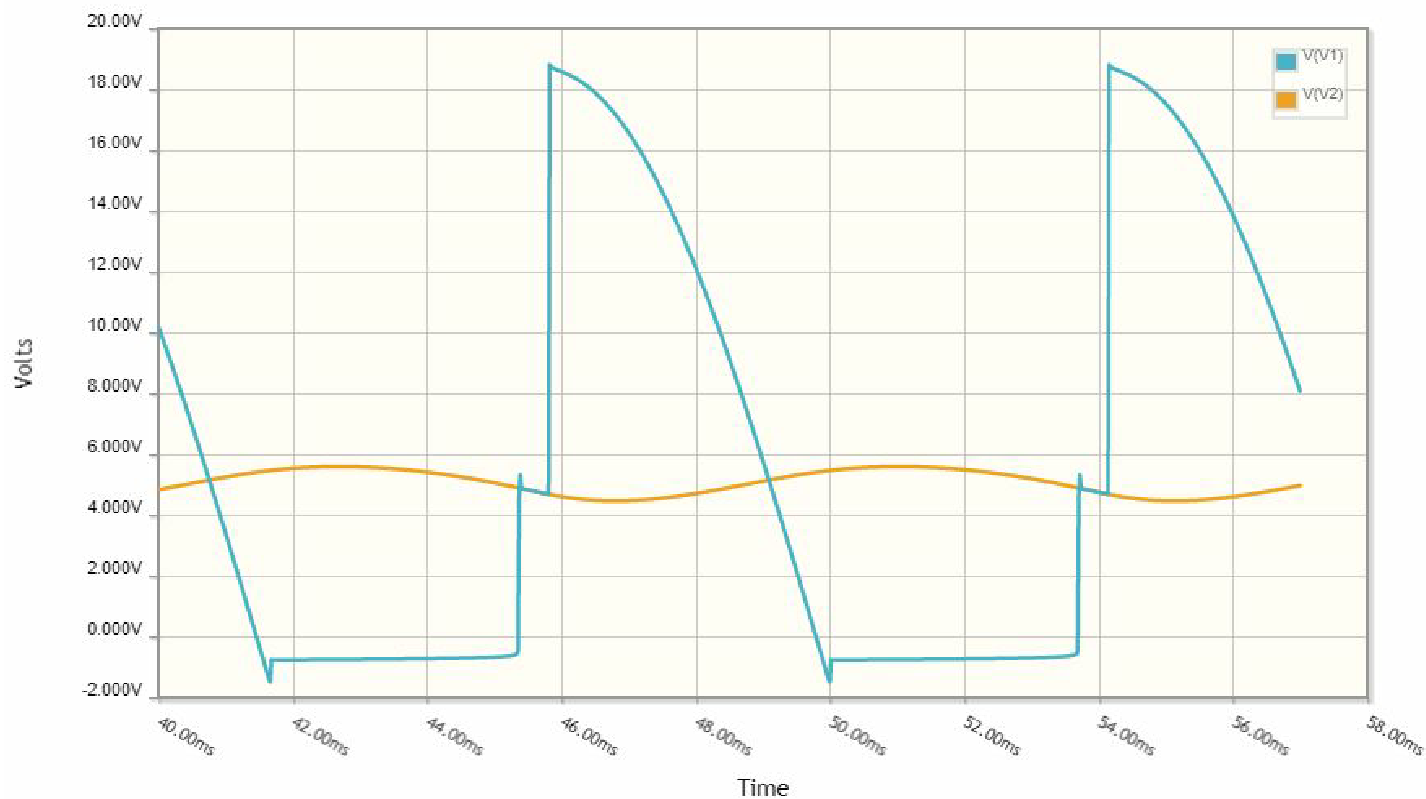
```
t = [0:0.001:1]';  
V1 = max(-0.7, 20*sin(pi*t) - 1.4);  
N = round(89.47/180 * 1000);  
V1(1:N) = -0.7;  
  
V1DC = mean(V1);  
V2DC = (100/110)*V1DC  
  
w = 2*pi*120;  
R1 = 1 ./ (1/100 + j*w*101.8e-6);  
R2 = 10 + j*w*0.3;  
  
V1ac = 2*mean(V1 .* exp(-j*2*pi*t));  
V1pp = 2*abs(V1ac);  
  
V2ac = ( 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)
- $V2(AC) = (\max - \min) = 1.12V_{pp}$ (1.00V_{pp} design)



AC to DC Converter (take 3)

- Remove the 5th diode

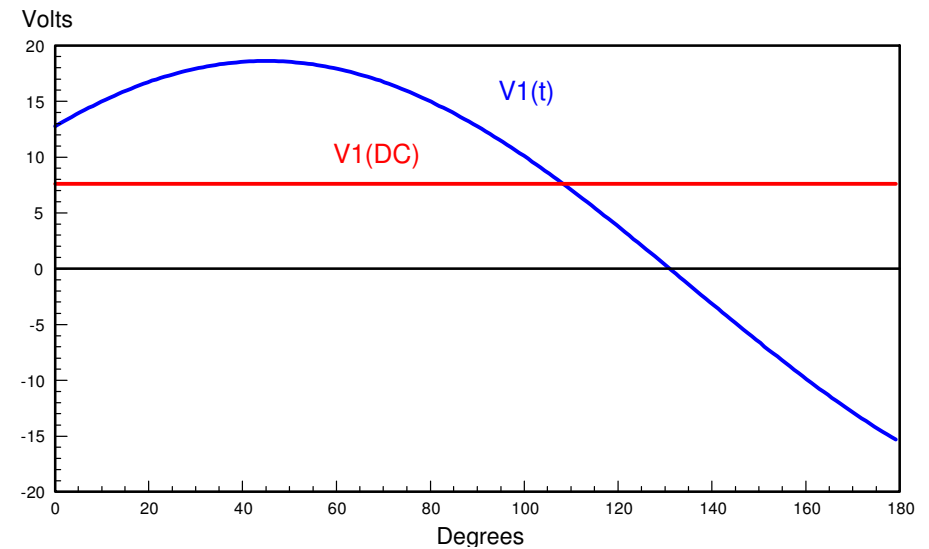
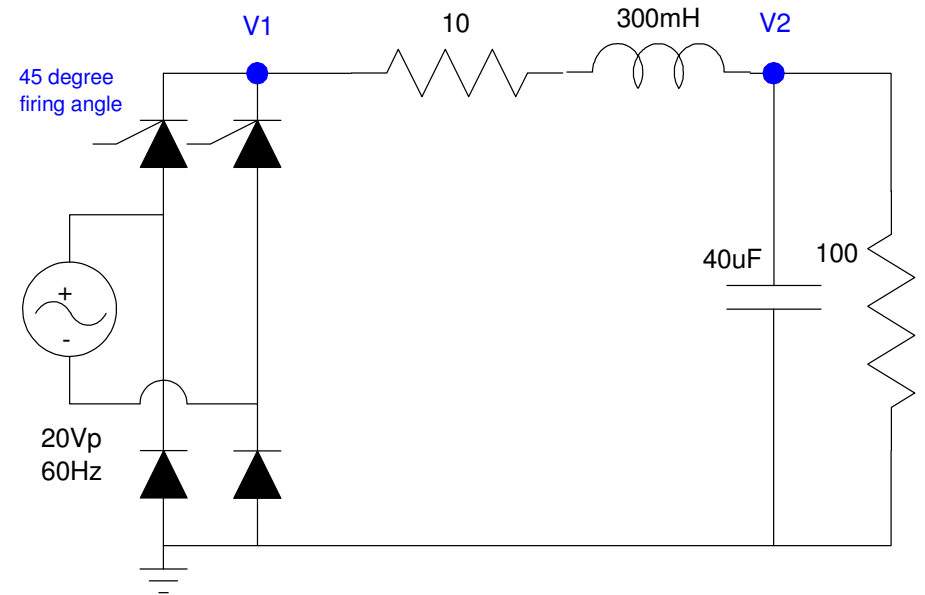
Changes

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

to

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

This results in V1 going negative



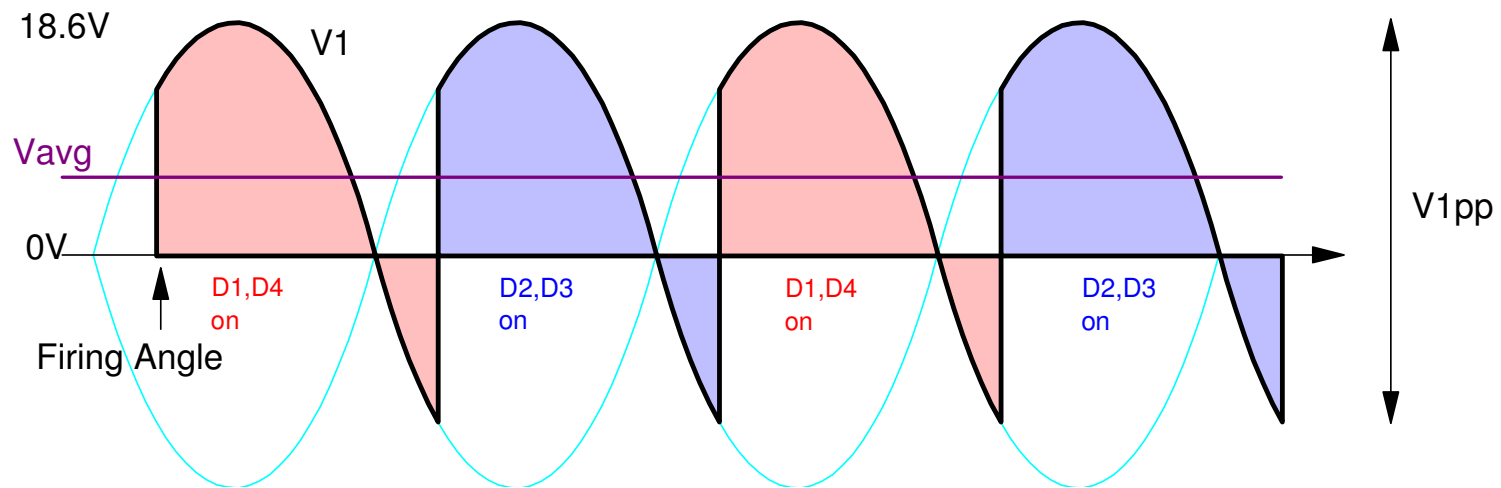
DC & AC Voltage at V1:

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

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

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

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



AC to DC Design Example (take 2):

Find the firing angle and C so that V2 is

- 10VDC
- 1Vpp ripple

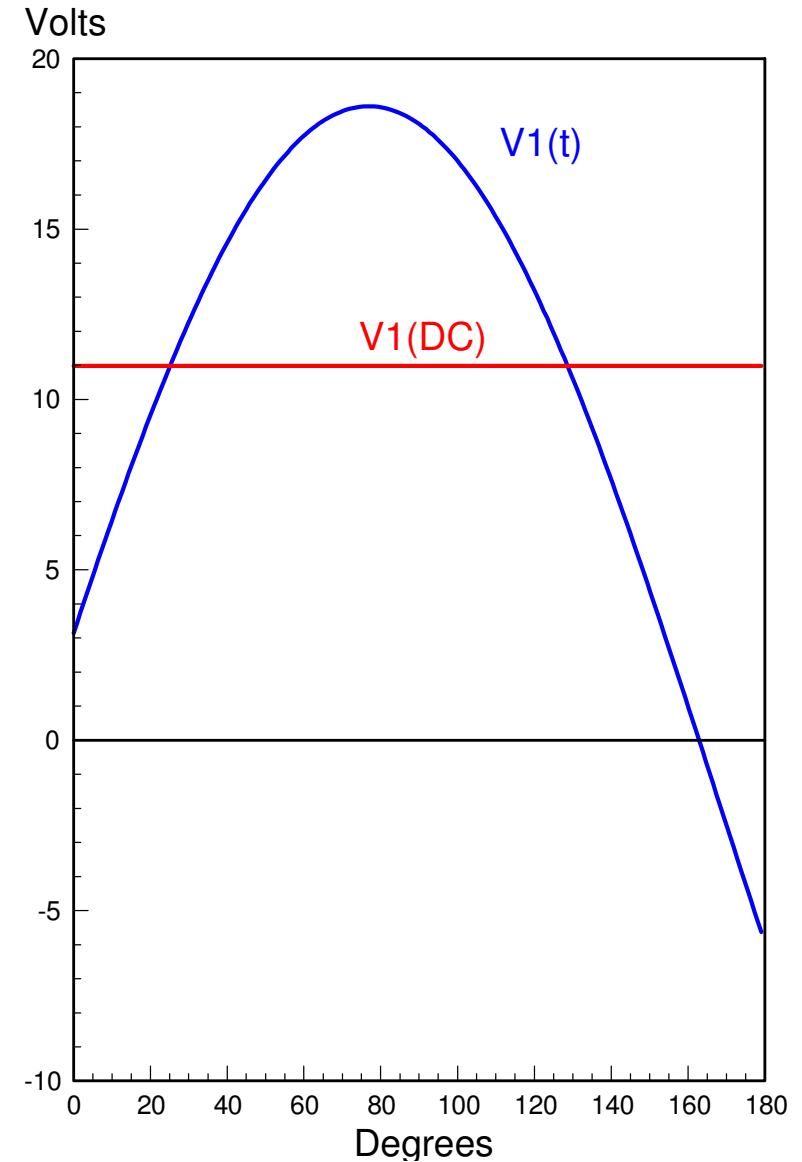
For $V_2(DC) = 10V$

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

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

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

$$\theta = 13.121^\circ$$



AC Analysis (L & C)

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

Using the Fourier Transform would be more accurate

If $C = 0$, the ripple at V2 is

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

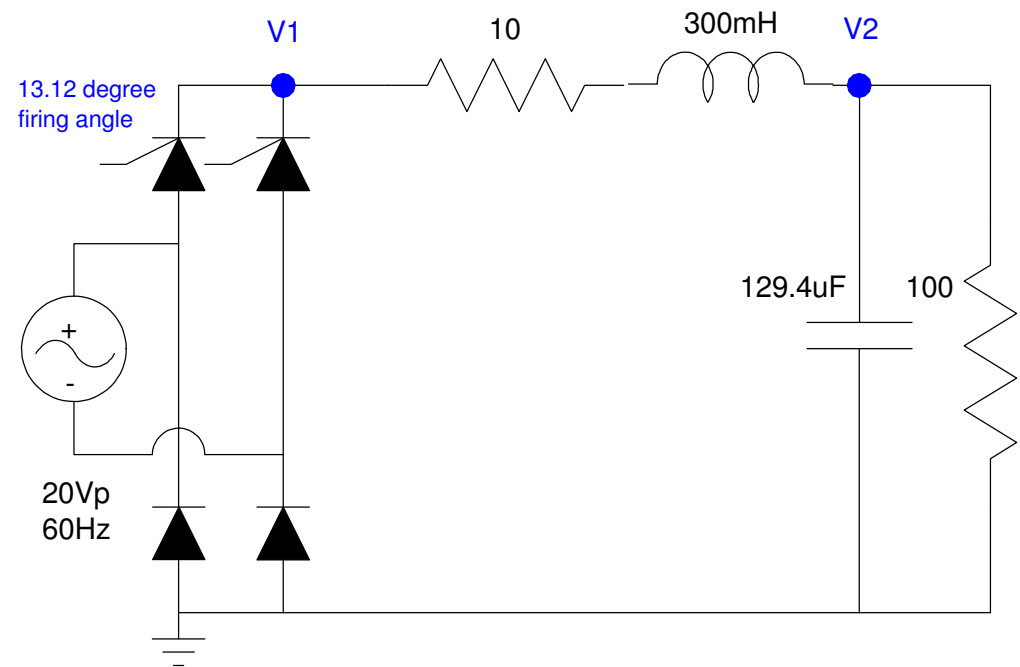
$$V_2(AC) = 9.756V_{pp}$$

C reduces R to set the ripple

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

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

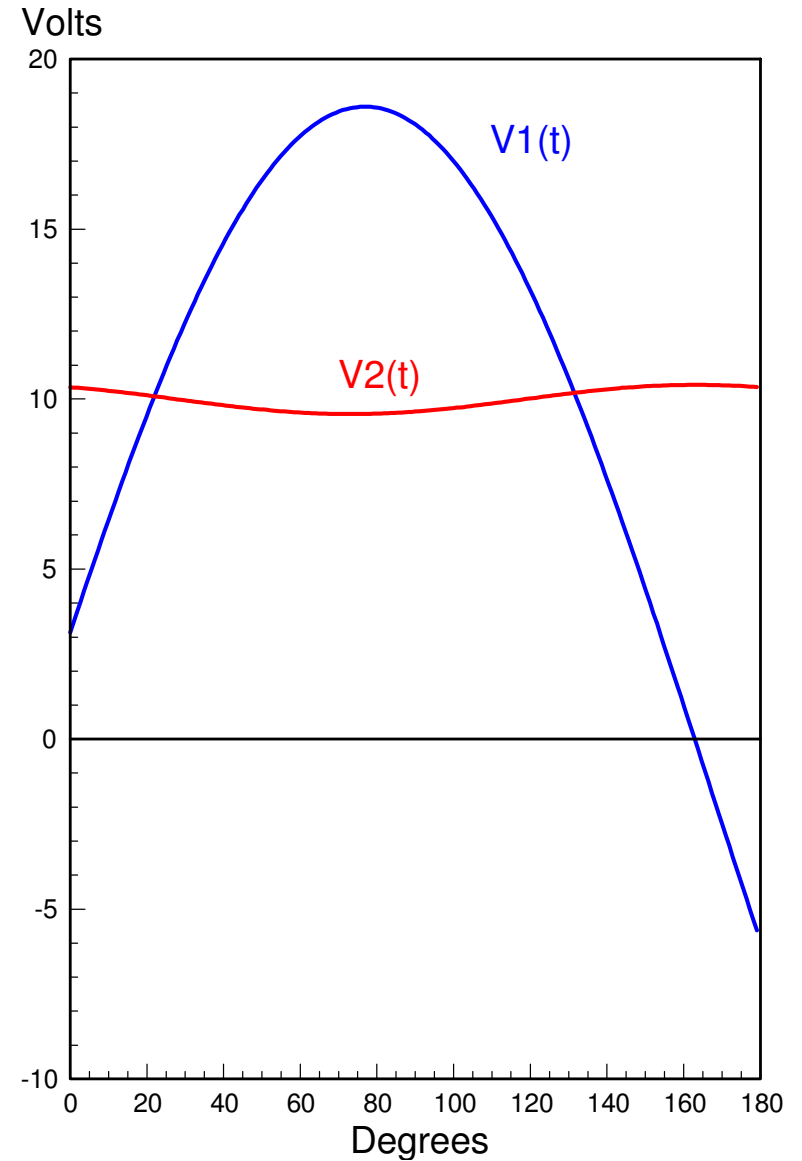
$$C = 129.4\mu F$$



Simulation Results

- $V2(\text{DC}) = 9.9891\text{V}$
- $V2(\text{AC}) = 0.8591\text{V}_{\text{pp}}$

```
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 lets 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
-