Avery Juwan T. Brillantes - 862243108

Thong Thach - 862224662

Lab 3 - Full-Wave Bridge Rectifiers in CCM and DCM Modes of Operation

Lab Section 021

TA’s Name: Zijin Pan

Introduction:

The objective of this lab is to learn about controlled converters, which include devices called rectifiers and inverters. We will understand how thyristors work in full-wave bridge converters. We will know the difference between rectifiers and inverters and how to switch between them. We will see how inductive AC sources affect things like time, voltage, and power. We will learn the two ways controlled converters can operate: continuous and discontinuous. We will use simulations to study circuits when they're really busy or not busy at all.

Theory:

PART 1: Full-Wave Controlled Converters in Continuous Conduction Mode (CCM)

Average output voltage:

$$(1.1) \quad V_d = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\gamma \, d\gamma = \frac{2V_m}{\pi}\cos\alpha, \text{ where } \gamma = \omega t$$

Power consumed by constant current source:

$$(1.4) \quad P = \frac{1}{2\pi}\int_0^{2\pi} v_d(\gamma)\, d\gamma = I_d V_d = \frac{2V_m I_d}{\pi}\cos\alpha$$

So that

$$(1.5) \quad \begin{cases} V_d \geq 0, & 0^0 \leq \alpha \leq 90^0 \quad \text{(rectifier mode)} \\ V_d < 0, & 90^0 < \alpha \leq 180^0 \quad \text{(inverter mode)} \end{cases}$$

Average voltage:

$$(1.7) \quad V_d = \frac{2V_m}{\pi}\cos\alpha - \frac{2}{\pi}\omega L_s I_d$$

PART 2: Controlled Converters in Continuous and DiscontinuousConduction Modes

<u>Continuous Conduction Mode ($i_0 > 0$)</u>

(2.4)

$$i_o = \frac{V_m}{Z}\sin(\omega t - \theta) - \frac{E}{R} + \left[I_{LO} + \frac{E}{R} - \frac{V_m}{Z}\sin(\alpha - \theta) \right] e^{-(R/L)(\pi/\omega - t)}, \quad \text{for } i_0 \geq 0$$

$$(2.5) \quad I_{LO} = I_{L1} = \frac{V_m}{Z}\frac{-\sin(\alpha - \theta) - \sin(\alpha - \theta)e^{-(R/L)(\pi/\omega)}}{1 - e^{-(R/L)(\pi/\omega)}} - \frac{E}{R}, \quad \text{for } i_0 \geq 0$$

where

$$(2.6) \quad I_{LO} = i_0(\omega t = \alpha) \text{ and } I_{L1} = i_0(\omega t = \pi + \alpha)$$

Discontinuous Conduction Mode ($i_0 = 0$)

$$(2.7) \quad I_{LO} = I_{L1} = \frac{V_m}{Z}\frac{-\sin(\alpha-\theta)-\sin(\alpha-\theta)e^{-(R/L)(\pi/\omega)}}{1-e^{-(R/L)(\pi/\omega)}} - \frac{E}{R}, \quad \text{for } i_0 = 0$$

The critical angle α_c at which I_{LO} becomes zero follows from (2.7):

$$(2.8) \quad 0 = \frac{V_m}{Z}\sin(\alpha-\theta)\left[\frac{1+e^{-(R/L)(\pi/\omega)}}{1-e^{-(R/L)(\pi/\omega)}}\right] + \frac{E}{R}$$

$$(2.9) \quad \alpha_c = \theta - \sin^{-1}\left[\frac{1-e^{-\frac{\pi}{\tan\theta}}}{1-e^{-\frac{\pi}{\tan\theta}}} \cdot \frac{x}{\cos\theta}\right], \quad x = \frac{E}{V_m}$$

Prelab:

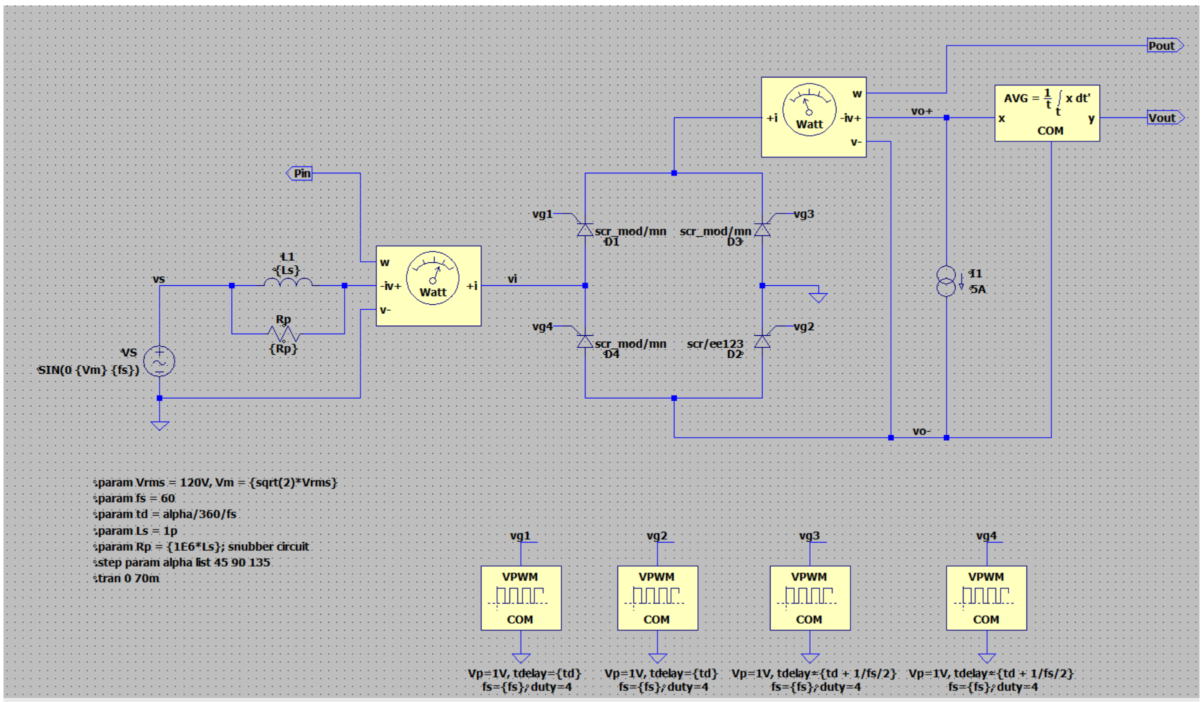
2. Why is the commutation time non-zero only when the ac source is inductive, and zero otherwise?

Commutation time is how long it takes for a semiconductor device, like a diode or thyristor, to turn off after the electric current switches direction. This is really important for keeping things safe, especially when dealing with reverse voltage. When an AC source is connected to something with coils, like a motor, the current doesn't immediately drop to zero when the voltage changes direction. This delay happens because of the coils. So, the semiconductor device needs to wait before turning off to avoid causing a short circuit. That waiting time is called commutation time, and it's not zero. So, commutation time matters because it keeps things safe when the current changes direction.

Design Calculations and Circuit Schematic, including Experimental Data and Data Analysis:

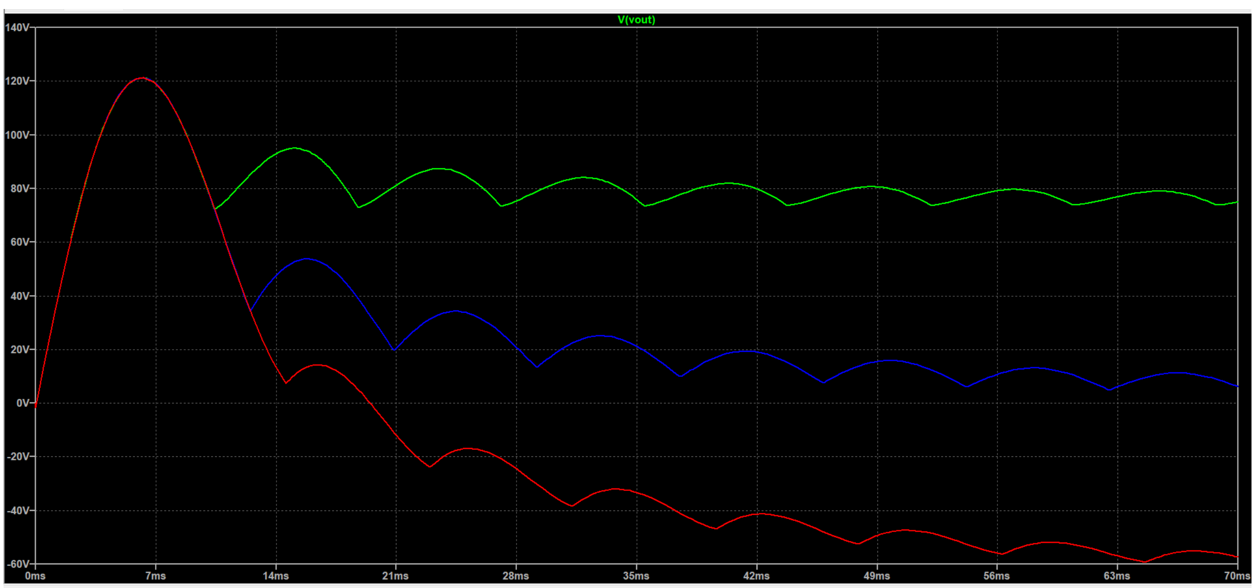
1.2

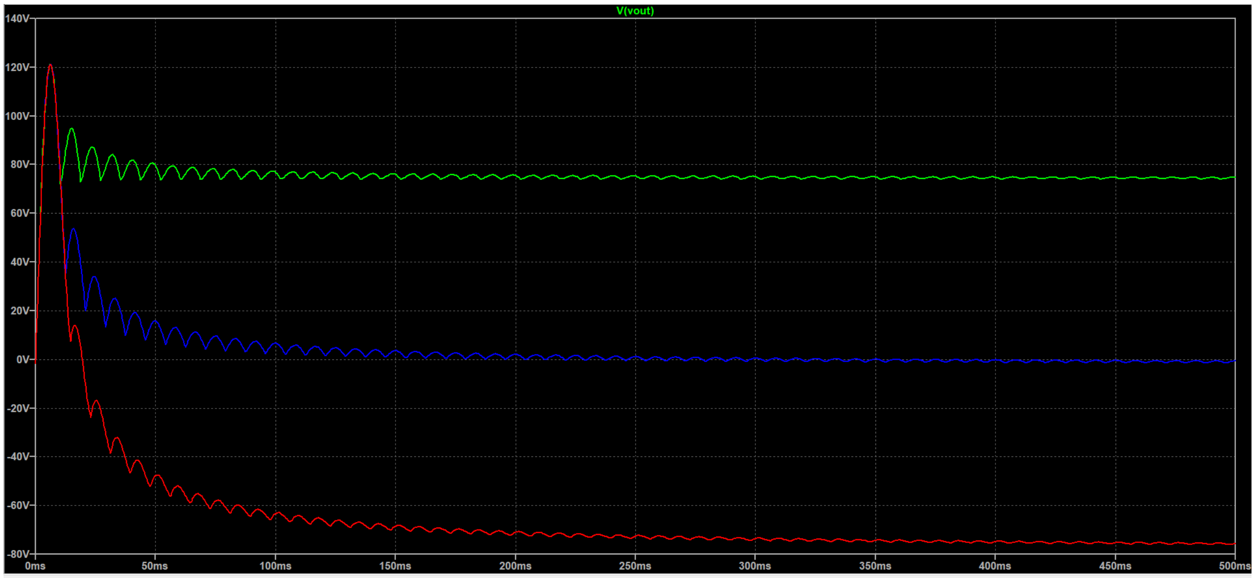
1)



4)

Experimental:





At α = 45°
V_d = 74.69 V

At α = 90°
V_d = -0.632 V

At α = 135°
V_d = -75.79 V

Theoretical:

$$(1.1) \qquad V_d = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\gamma d\gamma = \frac{2V_m}{\pi}\cos\alpha, \text{ where } \gamma = \omega t$$

At α = 45°
V_d = ((2*sqrt(2)*120)*cos(45)) / 3.14) = 76.39 V

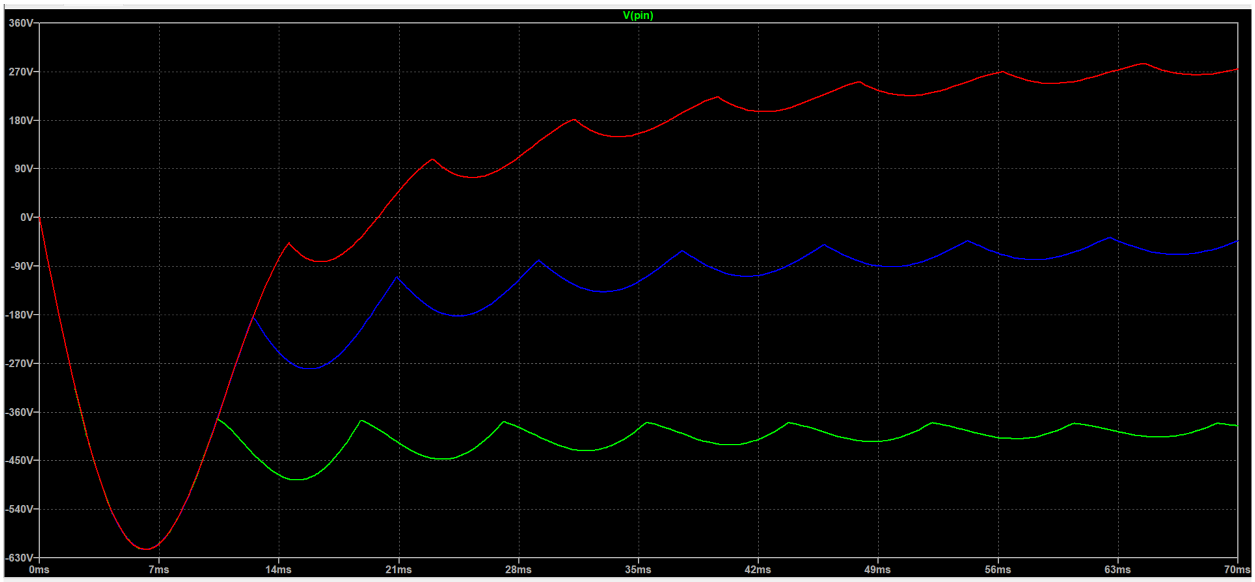
At α = 90°
V_d = ((2*sqrt(2)*120)*cos(90)) / 3.14) = 0 V

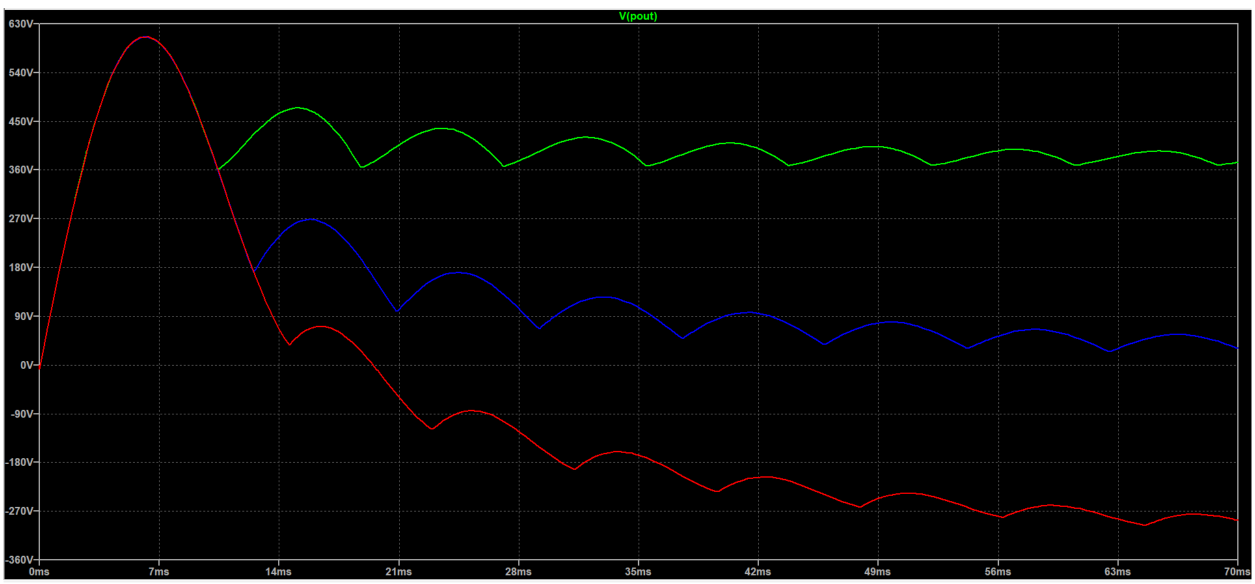
At α = 135°
V_d = ((2*sqrt(2)*120)*cos(135)) / 3.14) = -76.39 V

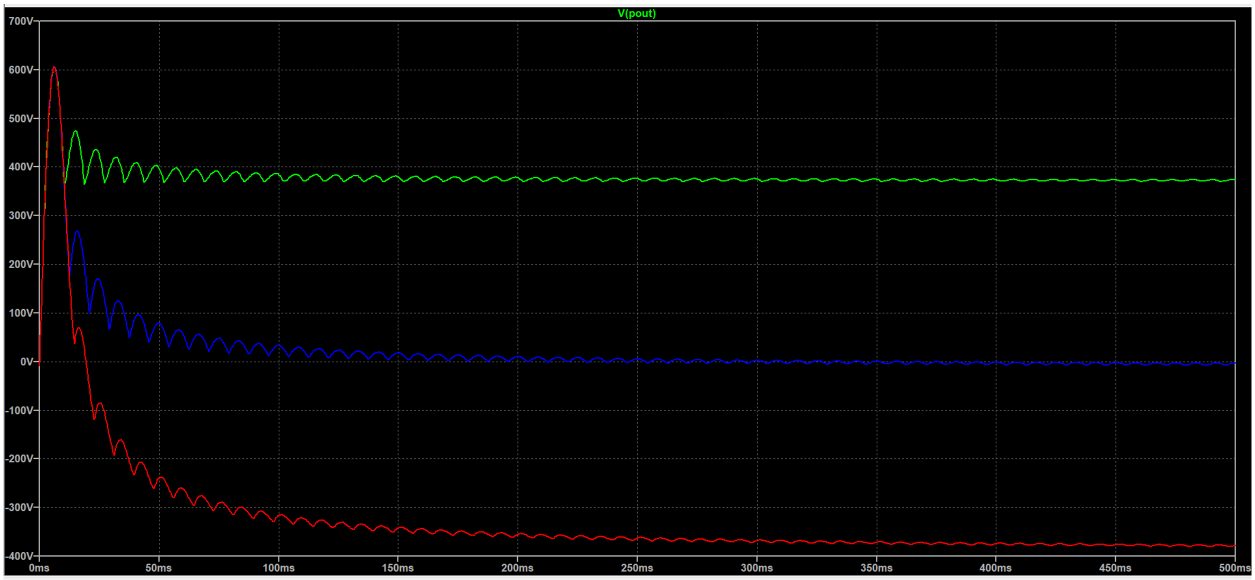
α = 45° both experimental and theoretical values are close to one another. Only off by about 2V. At α = 90° both experimental and theoretical values are close to one another. We can also see that during the experimental value it isn't exactly zero but a small negative voltage. At α = 135° both experimental and theoretical values are negative and close to one another. This suggests that our experimental values support the theoretical values.

5)

Experimental:







At α = 45°
P = 372.55 W

At α = 90°
P = -4.64 W

At α = 135°
P = -378.63 W

Theoretical:

$$(1.4) \quad P = \frac{1}{2\pi}\int_0^{2\pi} v_d(\gamma)d\gamma = I_d V_d = \frac{2V_m I_d}{\pi}\cos\alpha$$

At α = 45°
P = ((2*sqrt(2)*120*5)*cos(45)) / 3.14 = 381.97 W

At α = 90°
P = ((2*sqrt(2)*120*5)*cos(45)) / 3.14 = 0 W

At α = 135°
P = ((2*sqrt(2)*120*5)*cos(45)) / 3.14 = -381.97 W

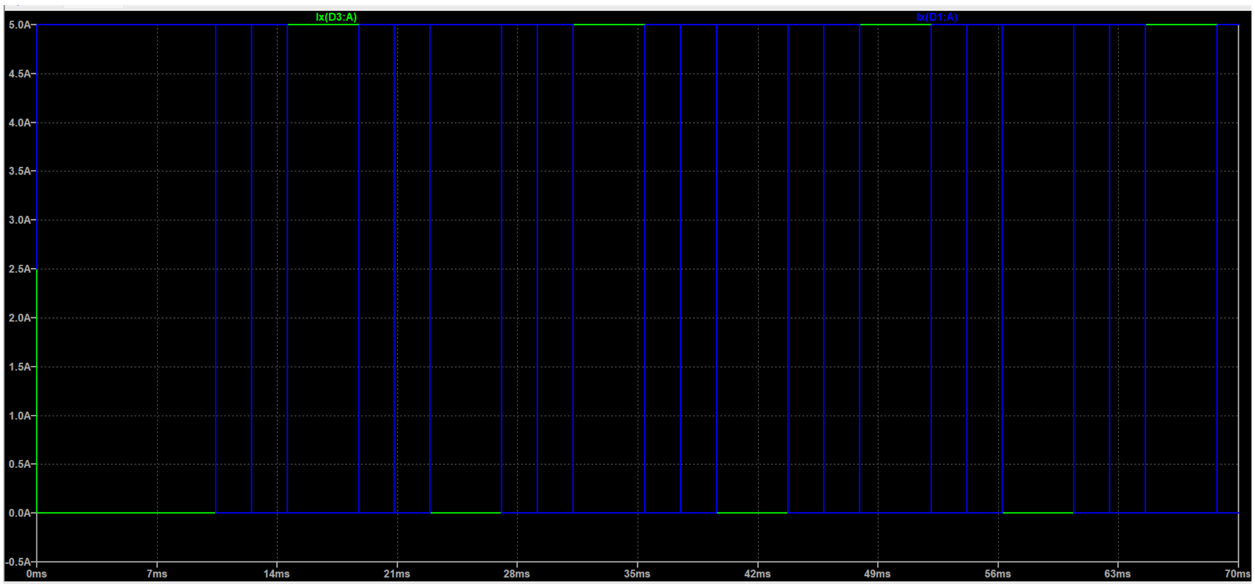
α = 45° both experimental and theoretical values are close to one another. Only off by about 9W and considering that we are dealing with hundreds of watts, 9W is a very small difference.. At α = 90° both experimental and theoretical values are close to one another. We can also see that the experimental value is -4W which is not 0W but is close enough. We can also notice that the source is actually consuming power here. At

α = 135° both experimental and theoretical values are negative and close to one another. Only off by about 3W. This suggests that our experimental values support the theoretical values.

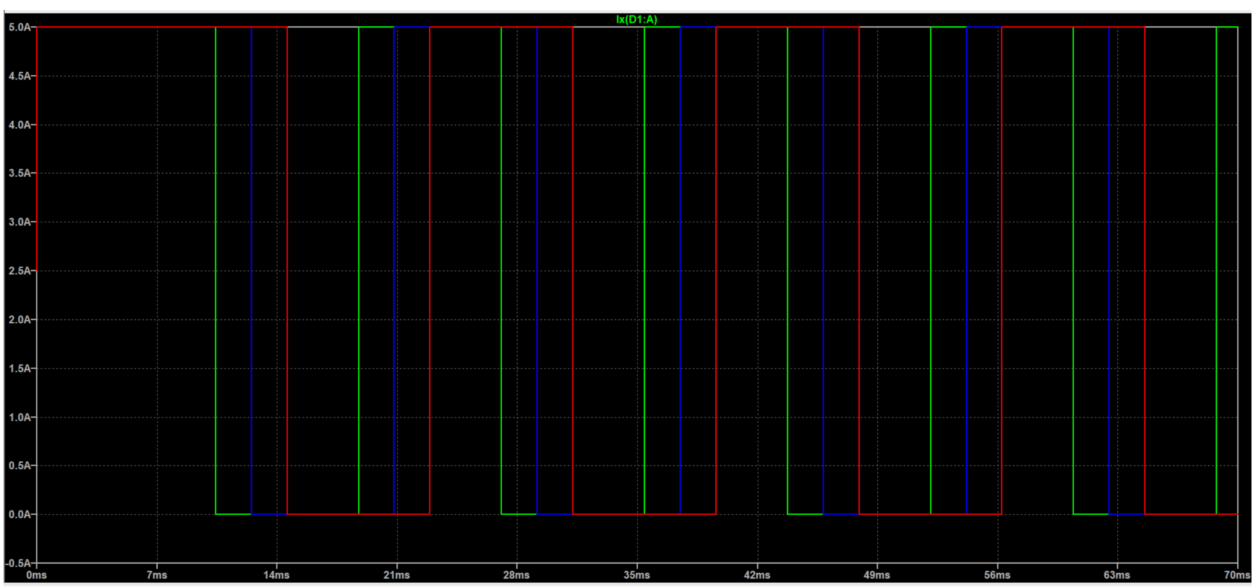
According to theory, the ac-source acts like power generators when α = 45º, 90º and acts like a power consumer when α = 135º. The dc-load acts like power generators when α = 135º and act like a power consumer when α = 45º, 90º. In our experiment we can see that 90º, the load actually generates power while the source consumes power even if it is only about 4W.

6)

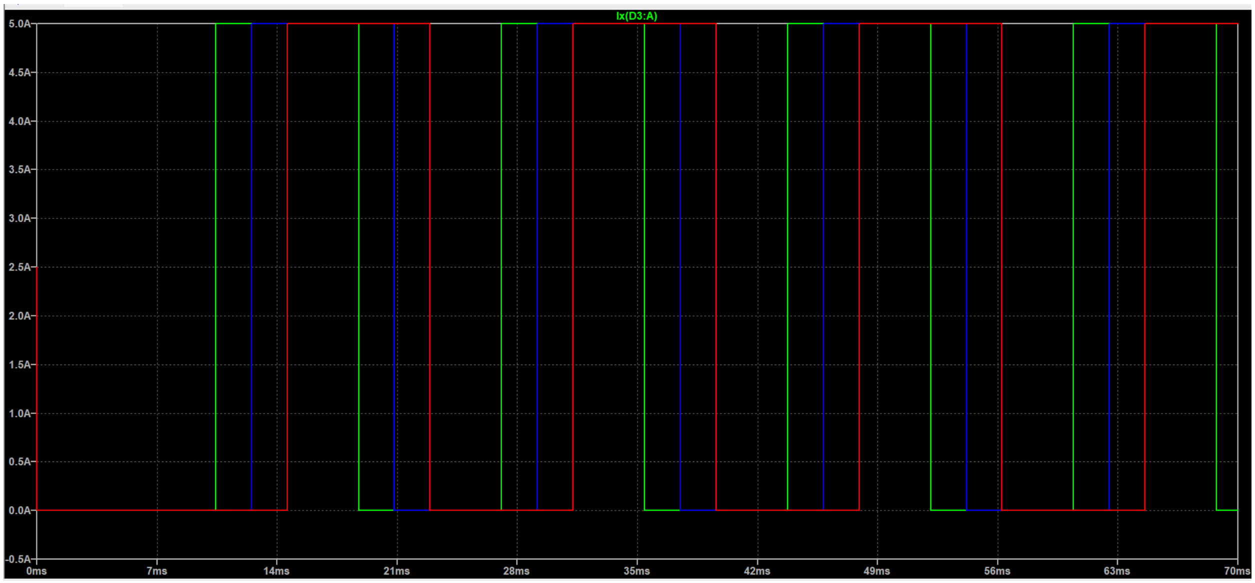
Both I_{D1} and I_{D3}



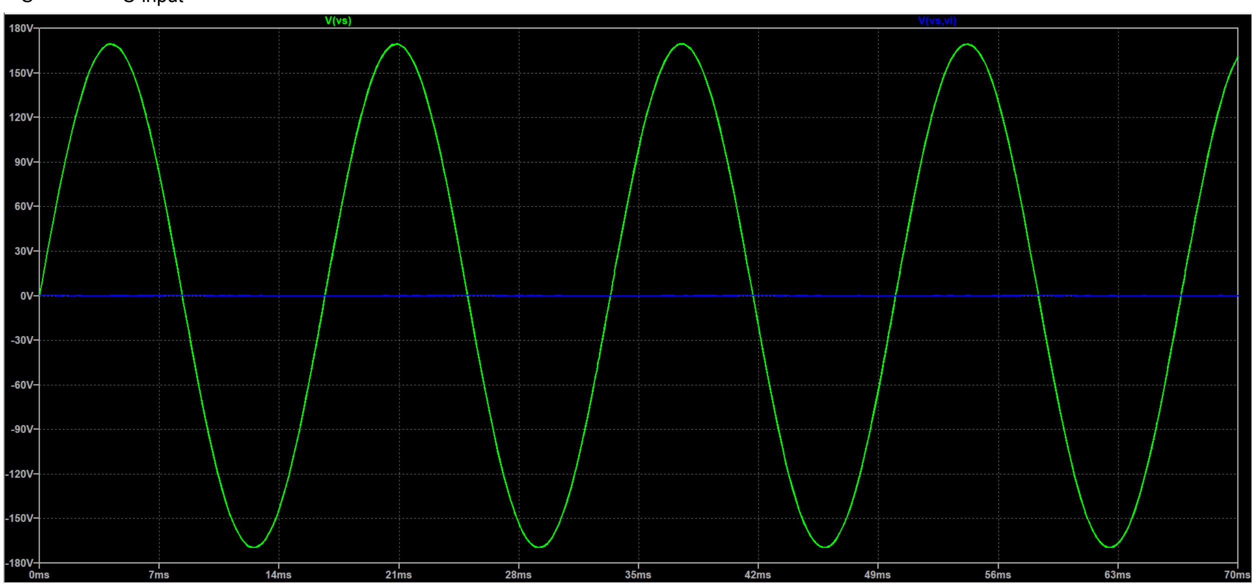
I_{D1}



I_{D3}

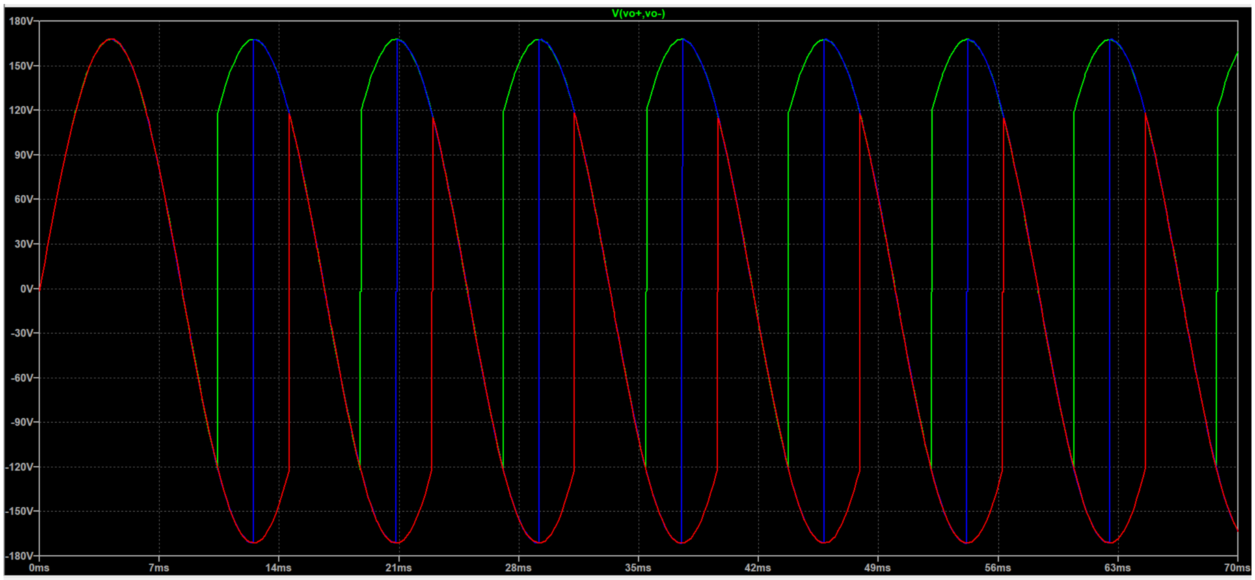


V_S and $V_{S\text{-input}}$



The commutation time is zero or very close to zero in all cases of α

7)



At α = 45°

Time = 8.31ms
D1 and D2 reversed biased, short (due to constant current)
D3 and D4 reversed biased, open

Time = 10.40ms
D1 and D2 reversed biased, open
D3 and D4 forward biased, short

Time = 16.64ms
D1 and D2 reversed biased, short (due to constant current)
D3 and D4 reversed biased, open

Time = 18.81ms
D1 and D2 forward biased, short
D3 and D4 reversed biased, open

At α = 90°

Time = 8.30ms
D1 and D2 reversed biased, short (due to constant current)
D3 and D4 reversed biased, open

Time = 12.50ms
D1 and D2 reversed biased, open
D3 and D4 forward biased, short

Time = 16.64ms
D1 and D2 reversed biased, short (due to constant current)
D3 and D4 reversed biased, open

Time = 20.89ms
D1 and D2 forward biased, short
D3 and D4 reversed biased, open

At α = 135°

Time = 8.30ms
D1 and D2 reversed biased, short (due to constant current)
D3 and D4 reversed biased, open

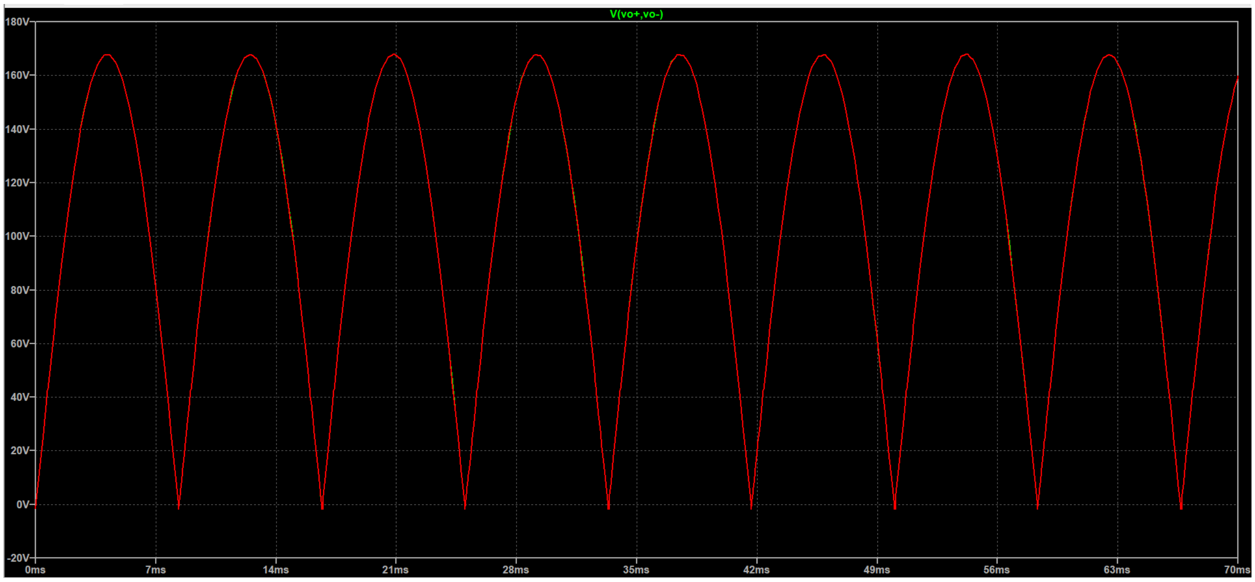
Time = 14.59ms
D1 and D2 reversed biased, open
D3 and D4 forward biased, short

Time = 16.62ms
D1 and D2 reversed biased, short (due to constant current)
D3 and D4 reversed biased, open

Time = 22.94ms
D1 and D2 forward biased, short
D3 and D4 reversed biased, open

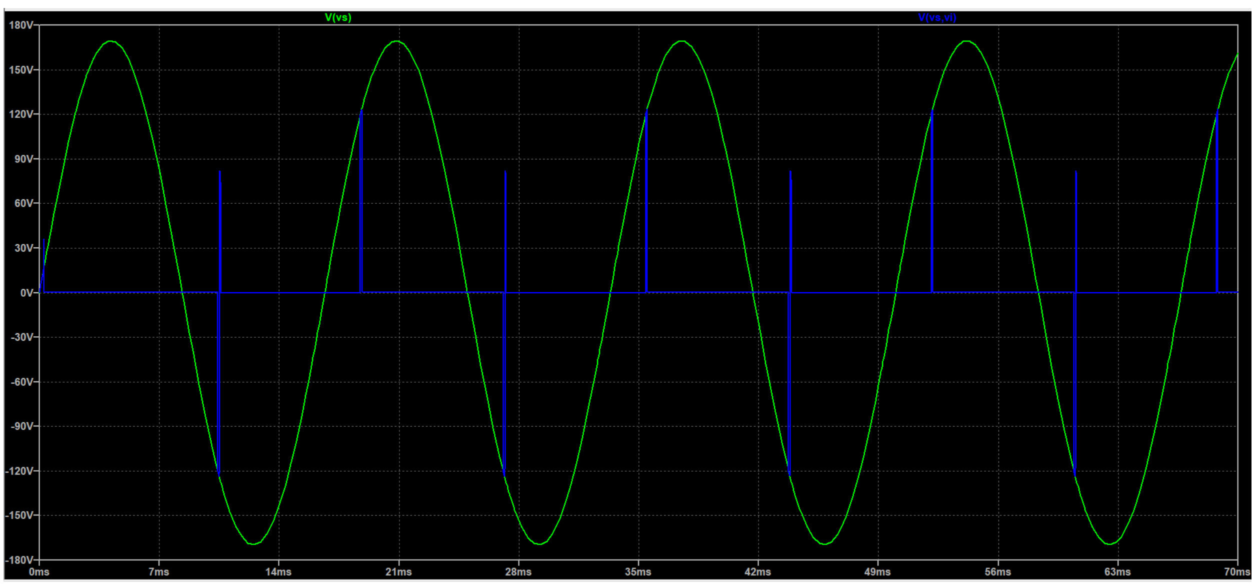
We can see that the first wave of the sine is always conducting. D1 and D2 are forced to a short due to the constant current which explains why there is negative voltage right before the thyristors are turned on. Then D1,D2 and D3,D4 alternate each wave forward biased and reverse biased modes. We can see that as the firing angle increases it spends less time in the positive voltage part of the graph.

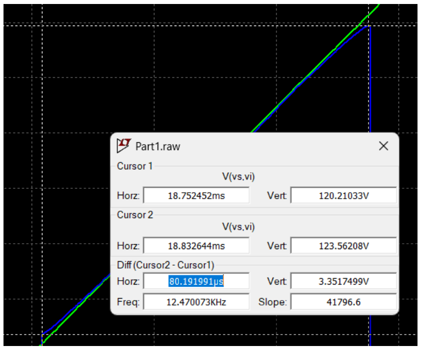
8)
At α = 0°



Yes, it looks like a full-wave bridge built with regular diodes

10)
Experimental:





t_{u45} = 80.19us

u = ωt_{u45} = (376.8rad/s)(80.19us) = 0.03 rads

Theoretical:

$$(1.6) \qquad u = \cos^{-1}\left[\cos\alpha - \frac{2\omega L_s I_d}{V_m}\right] - \alpha$$

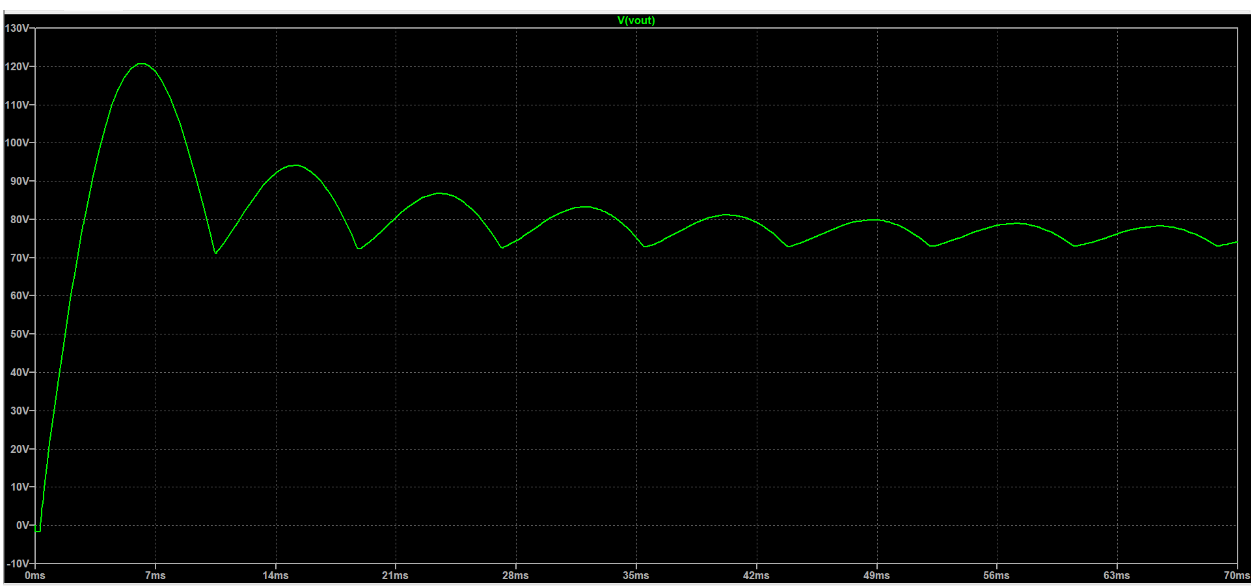
u = arccos(cos(3.14/4) - ((2*(2*3.14*60)*(1*10^-3)*5)/(sqrt(2)*120))) - 3.14/4 = 0.03 rads

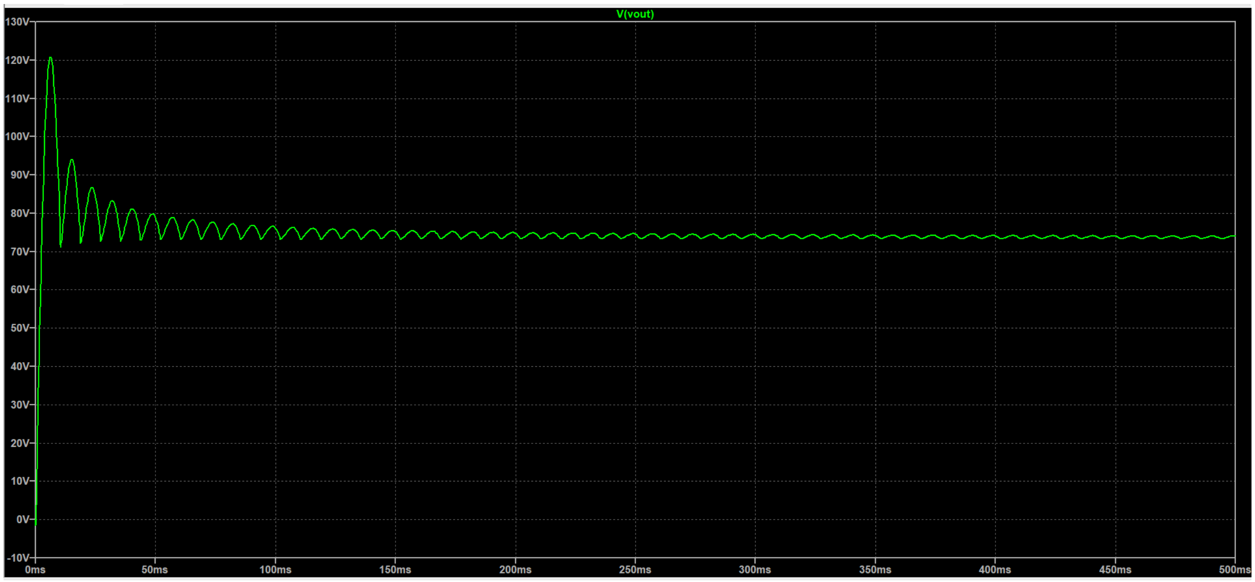
t_u = u/ω = 0.03 / (2*3.14*60) = 79.57 us

For the commutation angle, The theoretical value is the same as the experimental value. However, the commutation time in theory is a bit faster compared to the experiment.

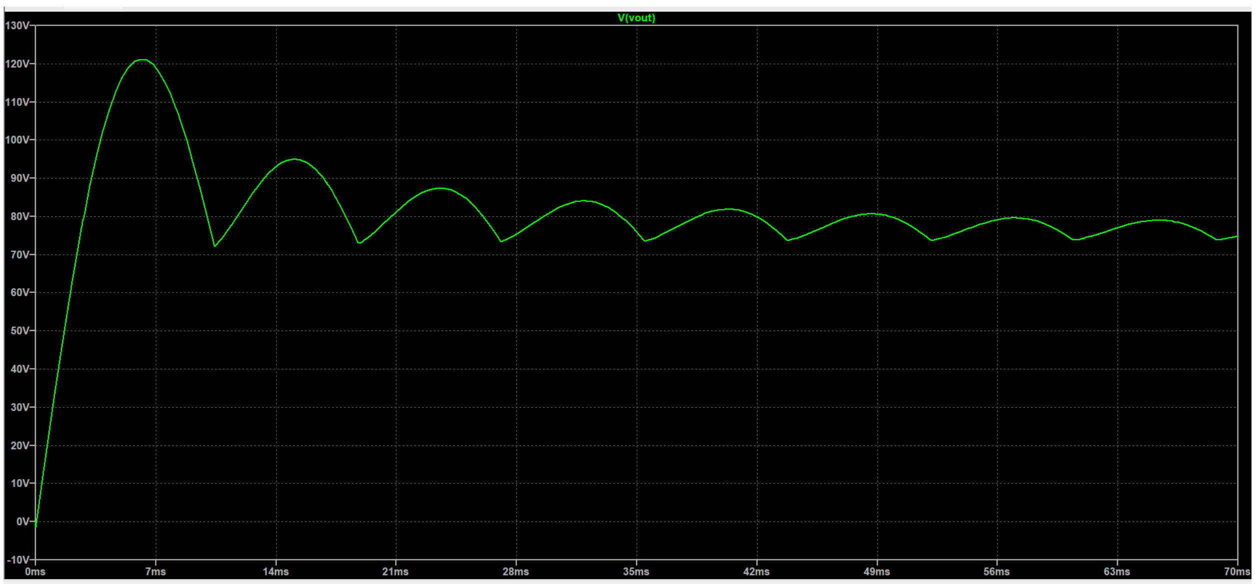
11)

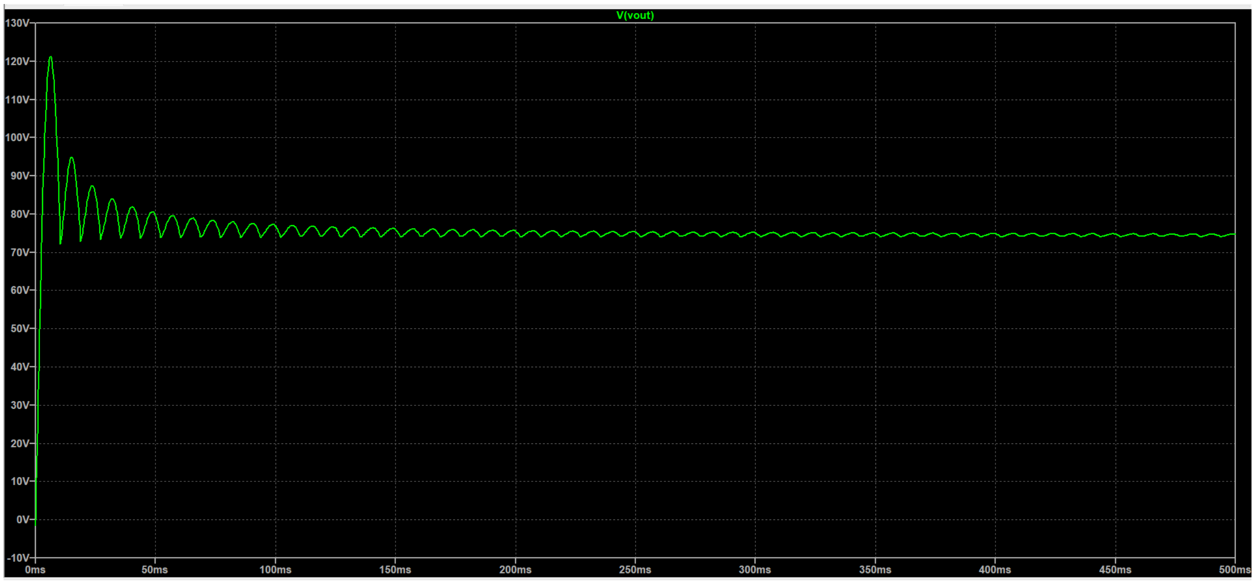
Inductive source





Non-inductive source





For Inductive
Vd = 73.99 V

For non-Inductive
V_d = 74.69 V

Theoretical:
For non-inductive

$$(1.1) \quad V_d = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\gamma \, d\gamma = \frac{2V_m}{\pi}\cos\alpha, \text{ where } \gamma = \omega t$$

V_d = ((2*sqrt(2)*120)*cos(45)) / 3.14) = 76.39 V

For inductive:

$$(1.7) \quad V_d = \frac{2V_m}{\pi}\cos\alpha - \frac{2}{\pi}\omega L_s I_d$$

V_d =(((2*sqrt(2)*120)*cos(3.14/4)) / 3.14) - ((2*(2*3.14*60)*(1*10^-3)*5) / 3.14)
= 75.19 V

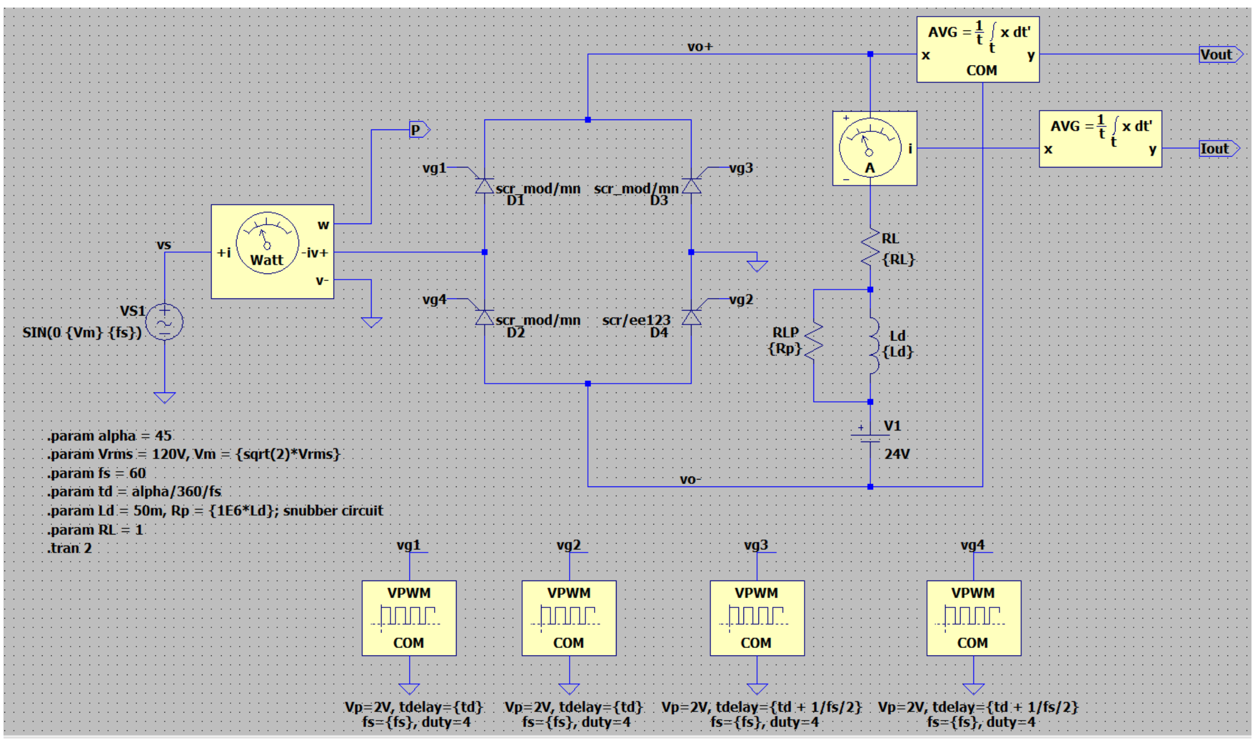
For the output voltage of an inductive source versus a non-inductive source, the difference between them may be due to the average output voltage resulting from the phase shift. However, since the Ls is small, that doesn't affect the average output voltage that much

12)

The firing angle affects whether the load or the source is generating or consuming power. It is important to note that at 90°, P = 0 but experimentally it is -4W meaning that the source is consuming power and the load is generating power. When inductance is very small commutation time is also very small. Having a constant current source will end up forcing some thyristors to conduct even if they are reversed biased. When firing angle is 0° then V_d will look like a full-wave bridge built with regular diodes The overall result is observing the change of circuit behavior in the delay angle. The commutation time from the simulation is exactly the same as the commutation time from the theoretical, u= 0.03 rads. The average voltage of the inductive is slightly smaller than the average voltage of the non-inductive by 1 V difference.

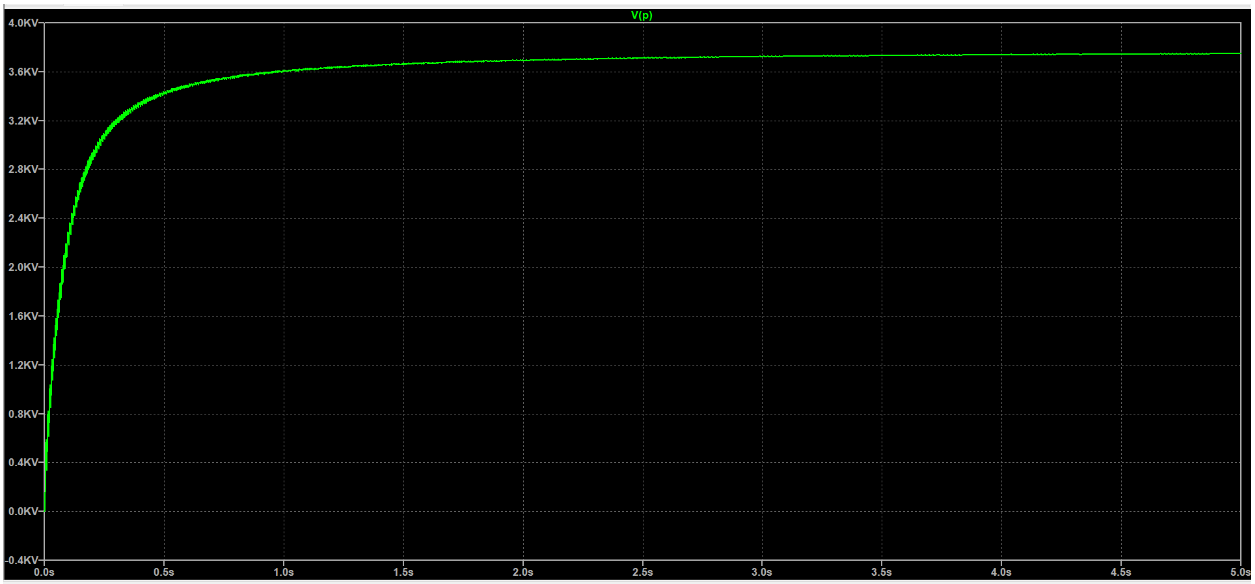
2.2

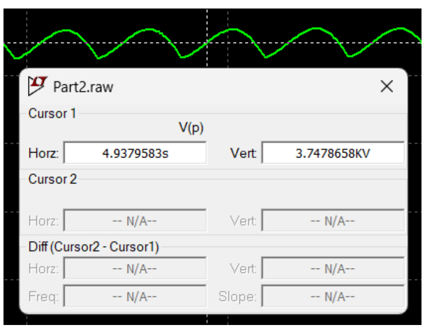
1)



3)

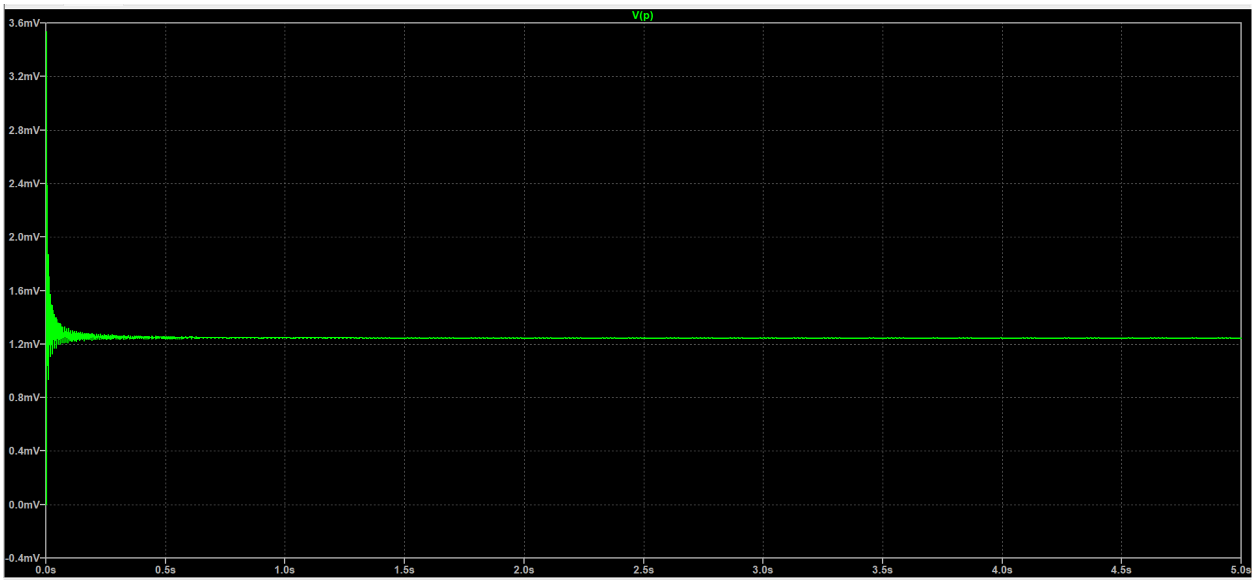
$R_L = 1$

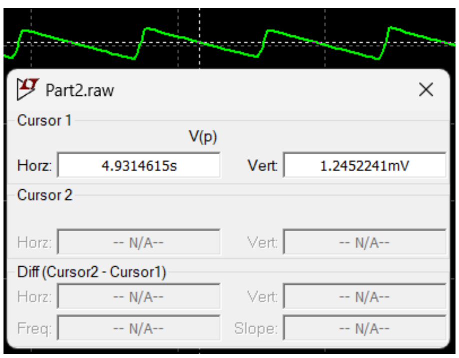




P_{AVE} = 3.75 KW

R_L = 1MΩ



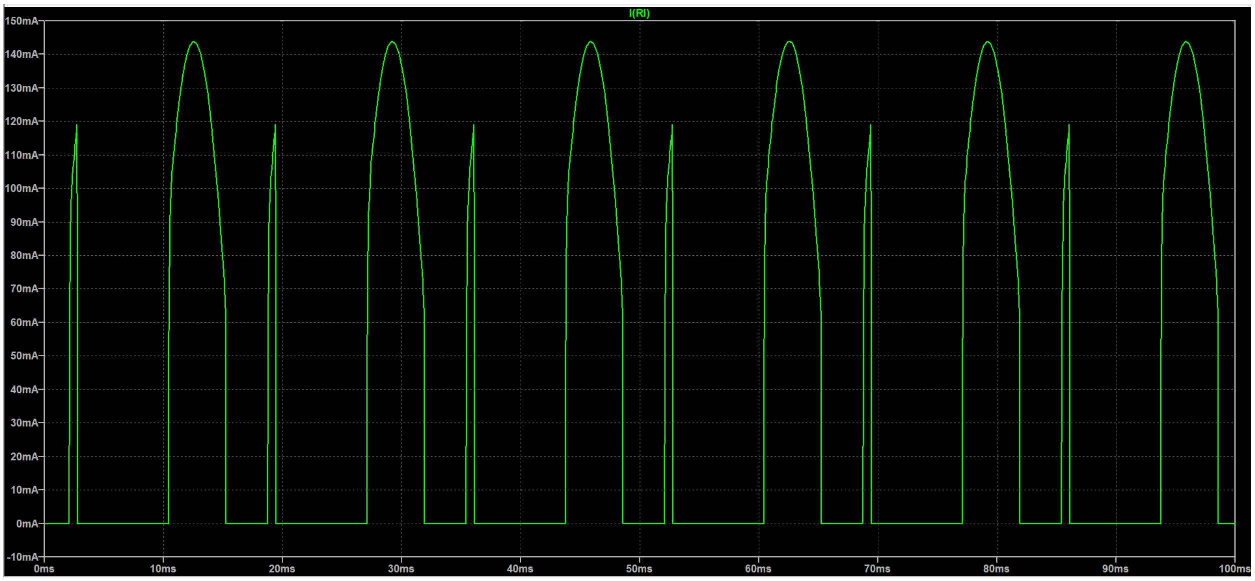


P_{AVE} = 1.25 mW

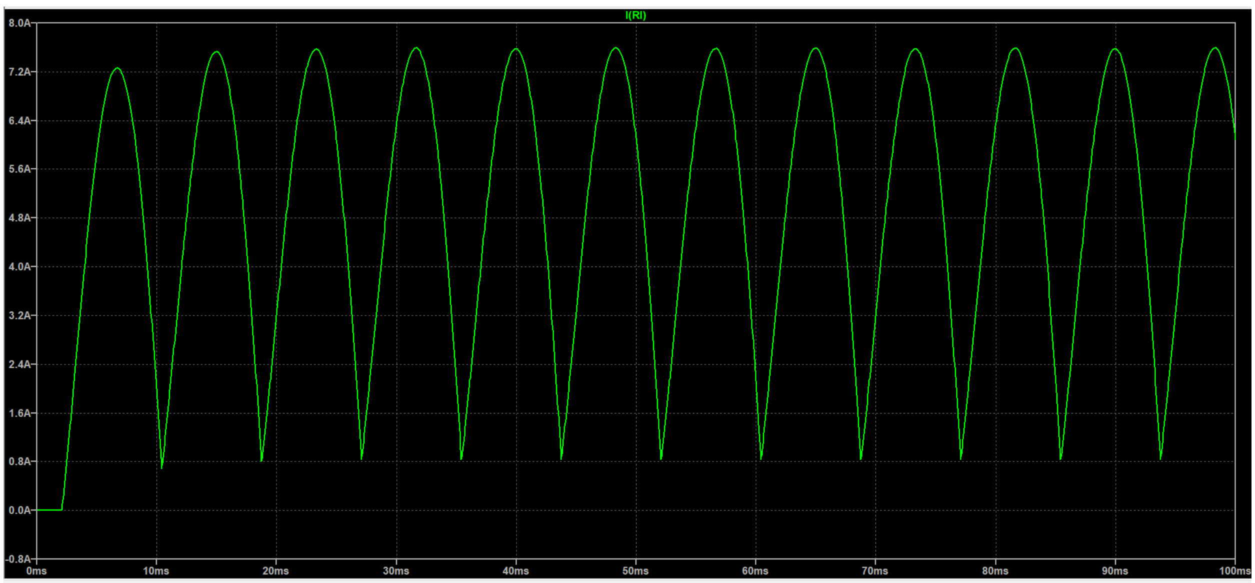
We can see that power consumption is larger when R_L is closer to 0, so in this case R_L = 1 has the larger power consumption. As a result we can verify that if R_L is very small then it is a fully loaded converter and a R_L is very large then it is an unloaded converter

4)

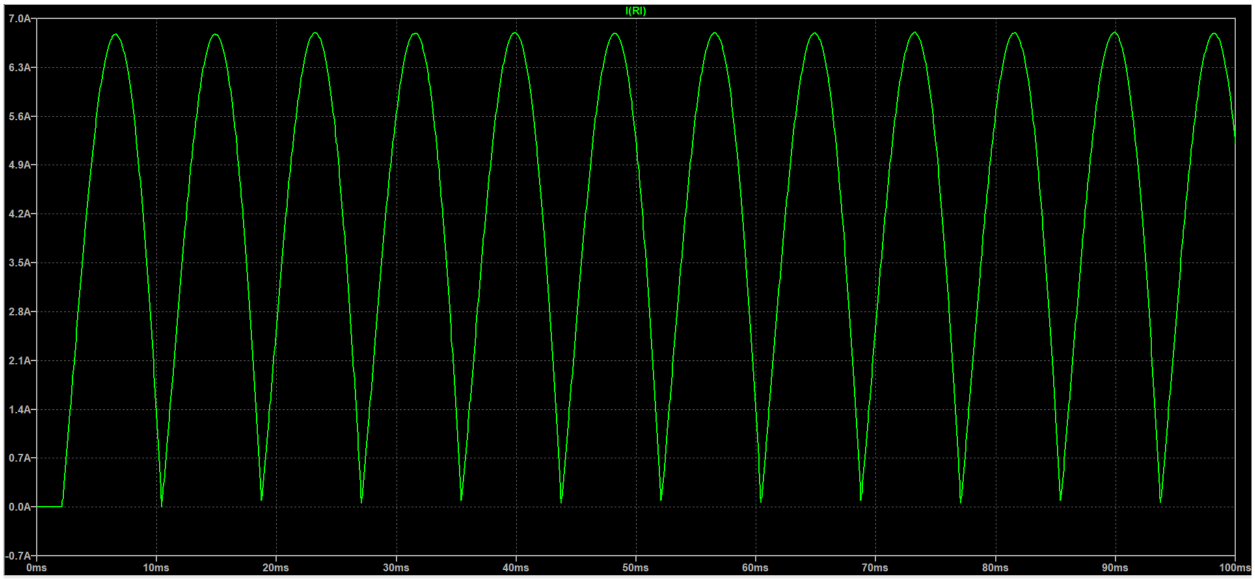
R = 1kΩ


I(Rl)
150mA
140mA
130mA
120mA
110mA
100mA
90mA
80mA
70mA
60mA
50mA
40mA
30mA
20mA
10mA
0mA
-10mA
0ms
10ms
20ms
30ms
40ms
50ms
60ms
70ms
80ms
90ms
100ms

R = 10Ω


I(Rl)
8.0A
7.2A
6.4A
5.6A
4.8A
4.0A
3.2A
2.4A
1.6A
0.8A
0.0A
-0.8A
0ms
10ms
20ms
30ms
40ms
50ms
60ms
70ms
80ms
90ms
100ms

R = 11.74Ω



R_L = 11.74Ω when the current just about hits 0A so this is the edge of CCM and DCM

5)

$$\theta = \tan^{-1}(\omega L / R)$$

Θ = arctan((2*3.14*60*50*10^-3) / 11.74 = 1.014 rads

$$(2.9) \quad \alpha_c = \theta - \sin^{-1}\left[\frac{1-e^{-\frac{\pi}{\tan\theta}}}{1-e^{-\frac{\pi}{\tan\theta}}} \cdot \frac{x}{\cos\theta}\right], \quad x = \frac{E}{V_m}$$

$$\Rightarrow \alpha_c = 1.014 - \sin^{-1}\left(\frac{1+e^{\frac{-\pi}{\tan(1.014)}}}{1-e^{\frac{-\pi}{\tan(1.014)}}} \cdot \frac{\frac{E}{V_m}}{\cos(1.014)}\right)$$

$$\Rightarrow \alpha_c = 1.014 - \sin^{-1}\left(\frac{1.1415}{0.8585} \cdot \frac{\frac{24}{120\sqrt{2}}}{0.5285}\right)$$

$$\Rightarrow \alpha_c = 1.014 - \sin^{-1}\left(1.33 \cdot \frac{0.1414}{0.5285}\right)$$

$$\Rightarrow \alpha_c = 1.014 - \sin^{-1}(0.3558)$$

$$\Rightarrow \alpha_c = 1.014 - 0.3638$$

$$\Rightarrow \alpha_c = 0.65023 \Rightarrow \boxed{\alpha_c = 37.255^\circ}$$

a_c = 37.26°

6)

Overall, when the current just about hits 0A so this is the edge of CCM and DCM, the R = 11.74Ω. When R is in the DCM mode, the critical angle is 37.26°.

Practice Problem Encounters:

The issue we encountered in this lab is that our teammate's laptop wasn't able to run the simulation. There were no other major issues encountered.

Conclusion:

In conclusion, the main objective of this lab is to understand the theoretical analysis behind Full-Wave Controlled Converters in Continuous Conduction Mode (CCM) and to run simulations to find the values for Vd, power consumed by the delay angle, and to determine the commutation time and commutation angle. The final part of the first section involves comparing the results between theoretical and simulation data.

For the second part of this lab, the primary objective is to comprehend Controlled Converters in Continuous and Discontinuous Conduction Modes theoretically, and then run simulations to determine the values of power consumed by the load and the load resistance RL at which the mode of operation is at the edge between CCM and DCM. From these results, the critical angle value is obtained. Finally, the theoretical and simulation results are compared. We successfully accomplished all the goals of this lab.