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

Lab Section 021

TA’s Name: Zijin Pan

Introduction:

The overall purpose of this lab is to understand the full-wave bridge rectifier characteristics. The maximum reverse voltage across diodes in the half-wave bridge is twice as full-wave bridge rectifiers. Because of that, full wave-bridge is suitable for high voltage applications. There are two modes inside full-wave bridge rectifiers: Continuous-current mode and Discontinuous-current mode. In the Continuous-current mode, the output current never goes to 0. In the Discontinuous-current mode, the output current is 0 for a period of time.

Theory:

The condition is met when in continuous-current mode:

$$(1.1) \quad \tau = RC \gg T = \frac{2\pi}{\omega}$$

$$(1.2) \quad \frac{3\omega L}{R} > 1$$

$$(1.3) \quad \omega L \gg \frac{1}{\omega C}$$

The output ripple current's amplitude has to be smaller than the output current I0:

$$I_0 = \frac{2V_m}{3\pi R}$$

$$I_1 = \frac{2V_m}{3\pi\omega L}$$

I ripple < I0:

1) Within CCM for ideal diodes, the load registers the absolute value of the input voltage source.

2) The disregard of transformers' inductive effects is justified by their non-storage of energy.

Prelab:

Demonstration that Figure 1.2 is in CCM mode

$$(1.1) \quad \tau = RC \gg T = \frac{2\pi}{\omega}$$

τ = RC >> T = (2π) / ω
τ = (5Ω)(2000μF) >> T = (2*π) / (2*π*60Hz)
τ = 0.1 >> T = 0.2

$$(1.2) \quad \frac{3\omega L}{R} > 1$$

(3ωL) / R > 1
(3*(2*π*60Hz)*(100mH)) / 5Ω > 1
22.608 > 1

$$(1.3) \quad \omega L \gg \frac{1}{\omega C}$$

(2*π*60Hz)*(100mH) >> 1 / ((2*π*60Hz)*(2000μF))
37.68 >> 1.33

Note: since we have a transformer V_m = 151V

$$(1.4) \quad I_0 = \frac{2V_m}{3\pi R}$$

I_0 = (2*151V) / (3*π*5Ω) = 6.41A

$$(1.5) \quad I_1 = \frac{2V_m}{3\pi\omega L}$$

I_1 = (2*151V) / (3*π*(2*π*60Hz)*100mH) = 0.85A

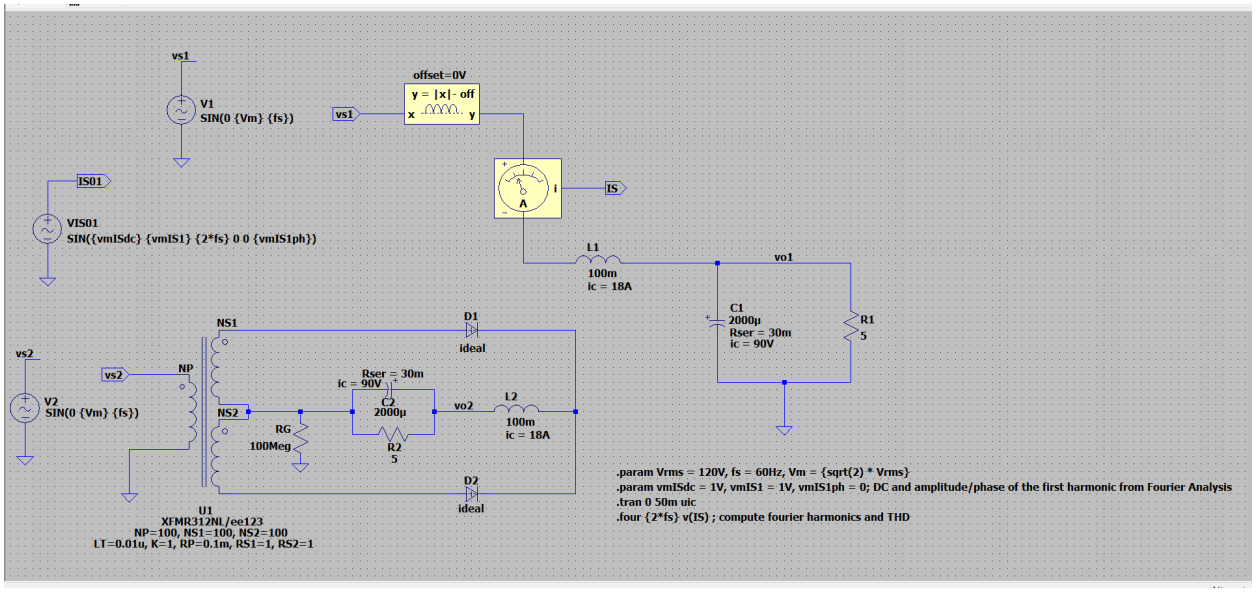
$$(1.6) \quad I_1 < I_0 \ \text{(CCM)}$$

0.85A < 6.41A
The circuit is in CCM Mode

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

1.2

1)



2) From Prelab

Note: since we have a transformer V_m = 151V

$$(1.4) \quad I_0 = \frac{2V_m}{3\pi R}$$

I_0 = (2*151V) / (3*π*5Ω) = 6.41A

$$(1.5) \quad I_1 = \frac{2V_m}{3\pi\omega L}$$

I_1 = (2*151V) / (3*π*(2*π*60Hz)*100mH) = 0.85A

$$(1.6) \quad I_1 < I_0 \ \text{(CCM)}$$

0.85A < 6.41A

The circuit is in CCM Mode

6)

SPICE Error Log: C:\Users\ajt_b\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part1.log

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Circuit: * C:\Users\ajt_b\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part1.asc

WARNING: Less than two connections to node IS01.  This node is used by VIS01.
Per .tran options, skipping operating point for transient analysis.
Ignoring empty pin current: Ix(u5:in)
N-Period=1
Fourier components of V(is)
DC component:18.0089

Harmonic            Frequency            Fourier            Normalized          Phas
 Number               [Hz]              Component            Component         [degr
    1              1.200e+02          9.612e-01          1.000e+00            -179
    2              2.400e+02          9.457e-02          9.839e-02            -179
    3              3.600e+02          2.648e-02          2.755e-02            -179
    4              4.800e+02          1.083e-02          1.127e-02            -179
    5              6.000e+02          5.271e-03          5.484e-03            -179
    6              7.200e+02          2.894e-03          3.011e-03            -178
    7              8.400e+02          1.933e-03          2.011e-03            -171
    8              9.600e+02          1.445e-03          1.504e-03             175
    9              1.080e+03          7.665e-04          7.975e-04             157
Total Harmonic Distortion: 10.301576%(10.301869%)



Date: Tue Apr 23 16:12:14 2024
Total elapsed time: 0.263 seconds.

tnom = 27
```

SPICE Error Log: C:\Users\ajt_b\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part1.log

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\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part1.asc

nnections to node IS01.  This node is used by VIS01.
ng operating point for transient analysis.
t: Ix(u5:in)

s)


ncy            Fourier            Normalized          Phase             Normalized
                Component           Component        [degree]           Phase [deg]
+02            9.612e-01          1.000e+00           -179.15°             0.00°
+02            9.457e-02          9.839e-02           -179.66°            -0.51°
+02            2.648e-02          2.755e-02           -179.60°            -0.45°
+02            1.083e-02          1.127e-02           -179.83°            -0.68°
+02            5.271e-03          5.484e-03           -179.61°            -0.46°
+02            2.894e-03          3.011e-03           -178.52°             0.63°
+02            1.933e-03          2.011e-03           -171.67°             7.48°
+02            1.445e-03          1.504e-03            175.03°           354.18°
+03            7.665e-04          7.975e-04            157.92°           337.07°
: 10.301576%(10.301869%)



 2024
 seconds.
```
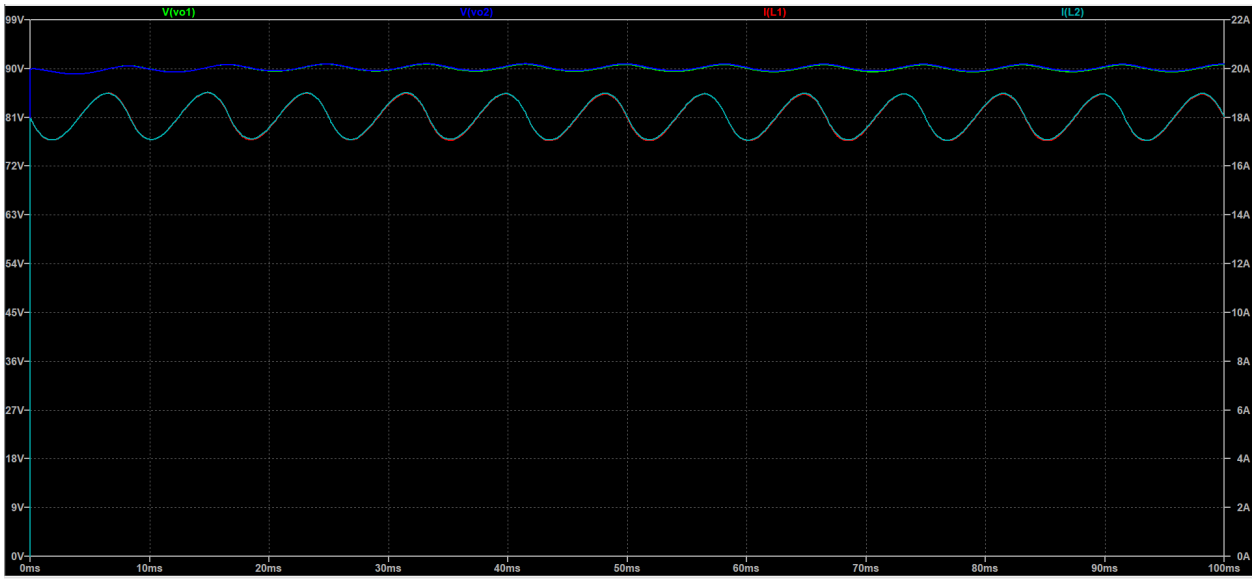
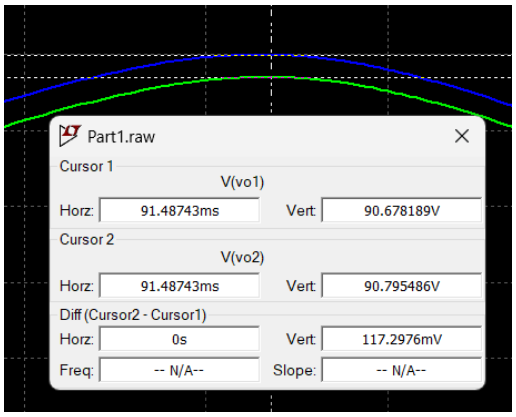

6)

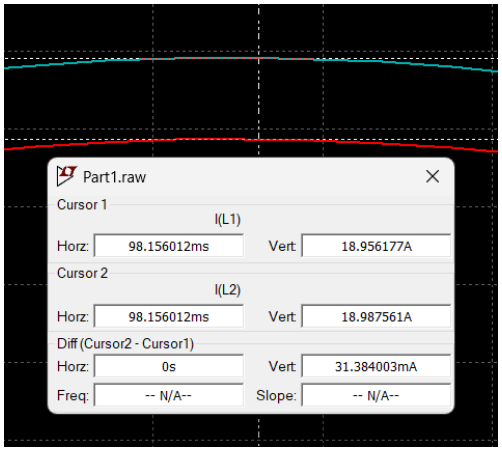
1. Phase = -179.15°= -3.13 rads, Amplitude = 0.96
2. DC of the Output Current = 18.01A
3. THD = 10.30%

9)
Experimental





We can see that the peaks of V_{o1} and V_{o2} are just slightly off by 0.12V



We can see that the peaks of I_{L1} and I_{L2} are just slightly off by 0.03A

Both the half bridge and full bridge are very close to one another

Theoretical
Note: Both the half-bridge and full bridge have the same equations for output voltage and current
Note: since we have a transformer V_m = 151V not 169.7

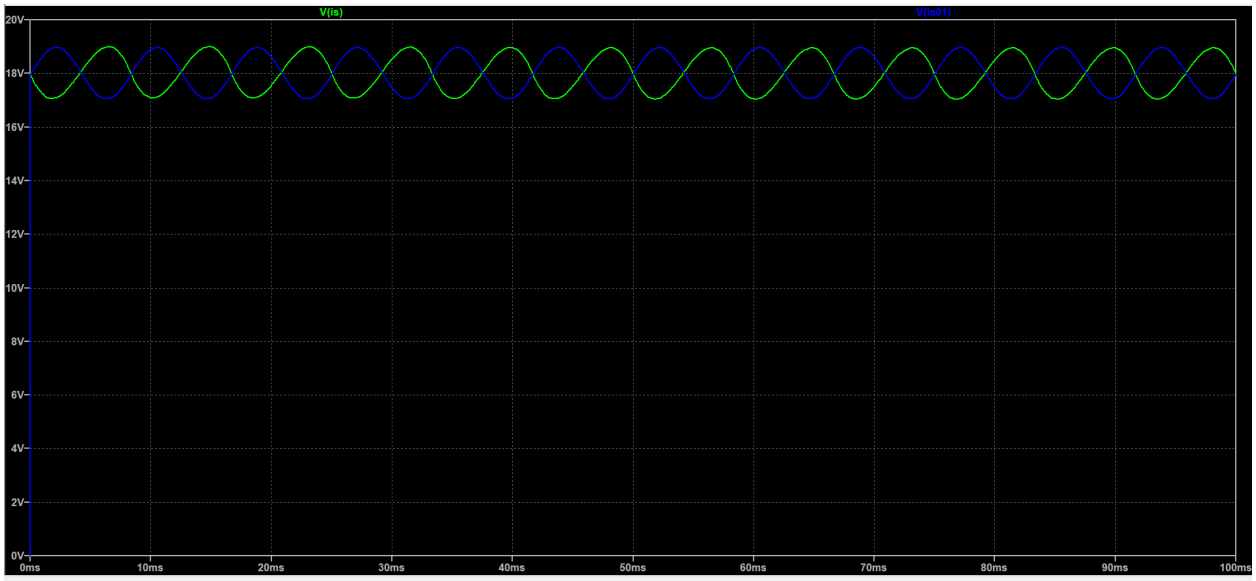
$$V_{o(dc)} = \frac{2}{2\pi}\int_0^{\pi} V_m \sin\theta d\theta = \frac{2V_m}{\pi}$$

$V_{o(dc)}$ = (2*151) / π = 95.54V

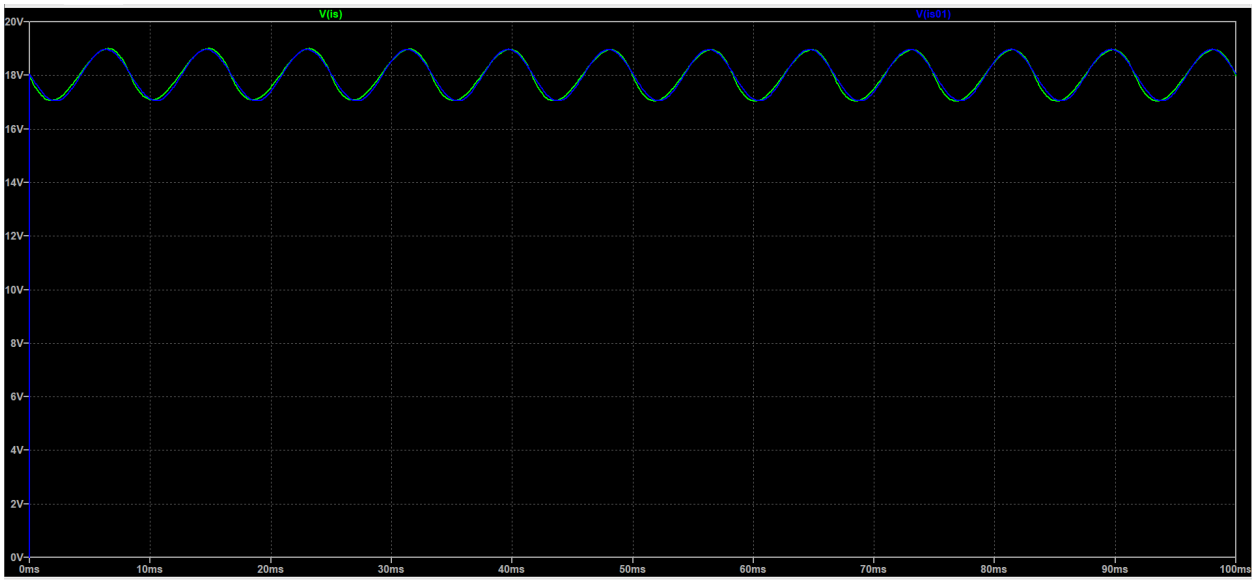
$$I_{o(dc)} = \frac{2V_m}{\pi R}$$

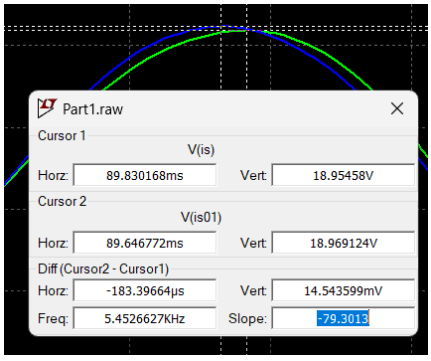
$I_{o(dc)}$ = (2*151) / (π*5) = 19.11A

Current output difference is about 0.12A and Voltage output difference is about 4.2V
These values are close enough to the experimental values
10)

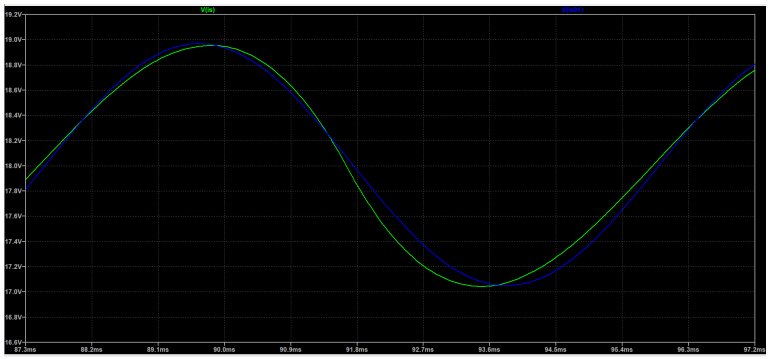


However if we flip the sign for vmIS1 we get





The amplitudes of both graphs are very similar to one another only different by about 0.01V



From here we can see that they are slightly out of phase

We notice that with the original value we get sine waves with opposite amplitudes but when we flip the sign of vmIS1 they are pretty much the same. The fundamental harmonic describes the waveform ripple well.

11)

6. THD = 10.30%

9. THD

I = 18.01 - 0.96cos(wt-3.13)

I_{RMS} = 18.02A

$I_{h1} = I_{DC} + I_1\cos(wt) = 6.41 + 0.85\cos(wt)$

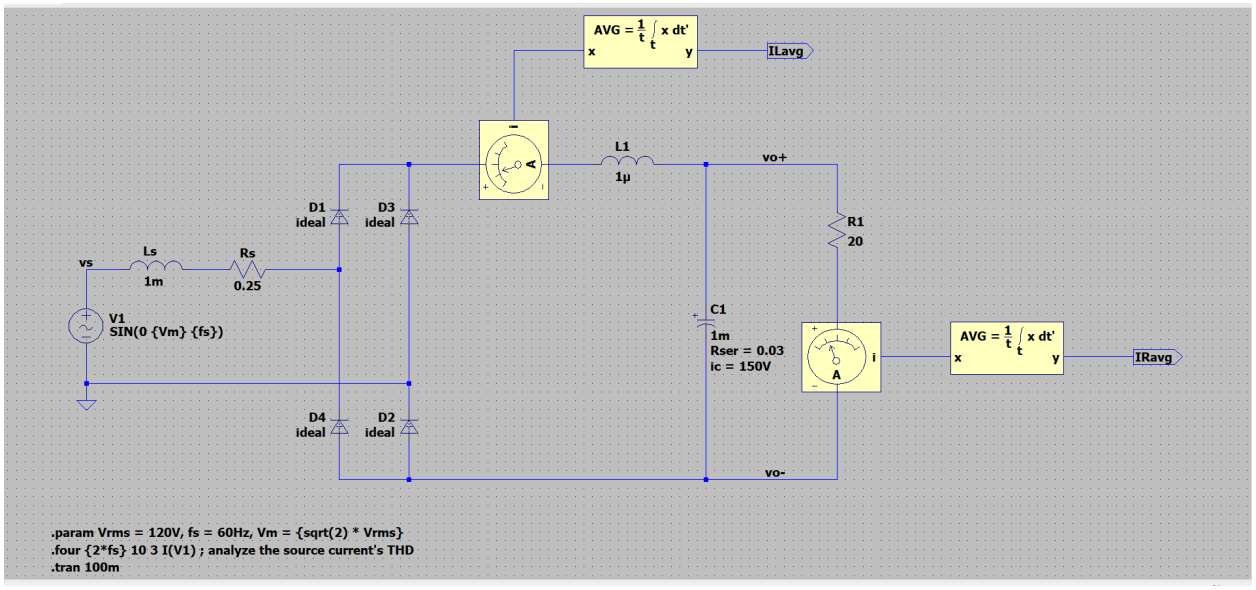
$I_{h1,RMS}$ = 6.44A

$I_{dis,\ RMS} = \text{sqrt}(I_{RMS}\text{^2} - I_{h1,RMS}\text{^2}) = \text{sqrt}(18.02\text{^} - 6.44\text{^2}) = 16.83A$

$THD = 100*(I_{h1,RMs} / I_{dis,RMS}) = 38.27\%$

According to this we have a 38% THD which I believe is wrong. This is probably due to some calculation error or by using the wrong I value.
It seems that a THD of 10.30% makes sense due to the relative smallness of the discrepancy between sine graphs

2.2



2) The Fourier series:

SPICE Error Log: C:\Users\ajt_b\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part2.log

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Circuit: * C:\Users\ajt_b\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part2.asc

Direct Newton iteration for .op point succeeded.
Ignoring empty pin current: Ix(u2:x)
Ignoring empty pin current: Ix(u4:x)
Ignoring empty pin current: Ix(u2:x)
Ignoring empty pin current: Ix(u4:x)
N-Period=3
Fourier components of I(v1)
DC component:2.57414

Harmonic            Frequency           Fourier           Normalized           Phas
 Number               [Hz]              Component          Component          [degr
    1              1.200e+02          4.477e+00          1.000e+00           -104
    2              2.400e+02          2.854e+00          6.375e-01             58
    3              3.600e+02          1.164e+00          2.600e-01           -146
    4              4.800e+02          2.787e-01          6.225e-02            -51
    5              6.000e+02          3.244e-01          7.247e-02             41
    6              7.200e+02          1.756e-01          3.923e-02            165
    7              8.400e+02          1.250e-01          2.793e-02           -115
    8              9.600e+02          1.084e-01          2.421e-02              2
    9              1.080e+03          6.615e-02          1.478e-02             94
   10              1.200e+03          7.048e-02          1.574e-02           -163
Total Harmonic Distortion: 69.745257%(420.412983%) PF=0.21108(0.0595517)



Date: Tue Apr 23 17:06:33 2024
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SPICE Error Log: C:\Users\ajt_b\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part2.log

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\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part2.asc

or .op point succeeded.
t: Ix(u2:x)
t: Ix(u4:x)
t: Ix(u2:x)
t: Ix(u4:x)

1)


ncy            Fourier           Normalized           Phase             Normalized
               Component          Component          [degree]           Phase [deg]
+02            4.477e+00          1.000e+00          -104.91°             0.00°
+02            2.854e+00          6.375e-01            58.19°           163.10°
+02            1.164e+00          2.600e-01          -146.75°           -41.83°
+02            2.787e-01          6.225e-02           -51.23°            53.68°
+02            3.244e-01          7.247e-02            41.10°           146.02°
+02            1.756e-01          3.923e-02           165.22°           270.13°
+02            1.250e-01          2.793e-02          -115.17°           -10.25°
+02            1.084e-01          2.421e-02             2.10°           107.01°
+03            6.615e-02          1.478e-02            94.25°           199.16°
+03            7.048e-02          1.574e-02          -163.45°           -58.53°
: 69.745257%(420.412983%) PF=0.21108(0.0595517)



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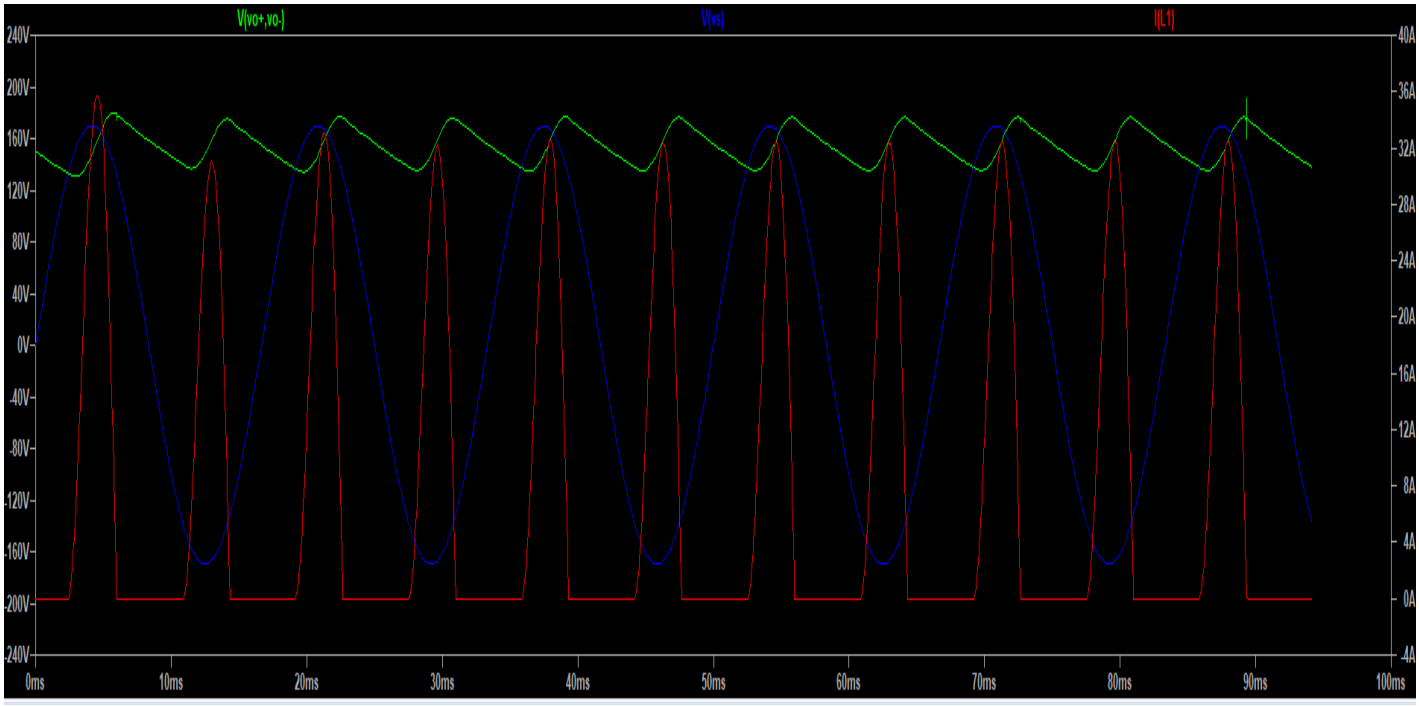
The waveform:



3)

SPICE Error Log: C:\Users\ajt_b\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part2.log

```
Circuit: * C:\Users\ajt_b\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part2.asc

Direct Newton iteration for .op point succeeded.
Ignoring empty pin current: Ix(u2:x)
Ignoring empty pin current: Ix(u4:x)
Ignoring empty pin current: Ix(u2:x)
Ignoring empty pin current: Ix(u4:x)
N-Period=3
Fourier components of V(vo+,vo-)
DC component:154.568

Harmonic            Frequency            Fourier            Normalized            Phas
 Number               [Hz]              Component            Component           [degr
    1              1.200e+02            1.776e+01           1.000e+00             170
    2              2.400e+02            5.681e+00           3.198e-01             -27
    3              3.600e+02            1.550e+00           8.723e-02             128
    4              4.800e+02            2.760e-01           1.554e-02            -133
    5              6.000e+02            2.558e-01           1.440e-02             -41
    6              7.200e+02            1.121e-01           6.310e-03              84
    7              8.400e+02            6.981e-02           3.930e-03             160
    8              9.600e+02            5.556e-02           3.127e-03             -79
    9              1.080e+03            3.100e-02           1.745e-03              12
   10              1.200e+03            3.112e-02           1.752e-03             117
Total Harmonic Distortion: 33.223681%(33.224455%)



Date: Tue Apr 30 13:48:21 2024
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SPICE Error Log: C:\Users\ajt_b\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part2.log

```
\Documents\LTspiceXVII\Schematics\EE123_Lab3\Part2.asc

or .op point succeeded.
t: Ix(u2:x)
t: Ix(u4:x)
t: Ix(u2:x)
t: Ix(u4:x)

o+,vo-)


ncy            Fourier            Normalized            Phase              Normalized
                Component           Component          [degree]            Phase [deg]
+02            1.776e+01           1.000e+00            170.18°              0.00°
+02            5.681e+00           3.198e-01            -27.30°           -197.47°
+02            1.550e+00           8.723e-02            128.63°            -41.55°
+02            2.760e-01           1.554e-02           -133.91°           -304.09°
+02            2.558e-01           1.440e-02            -41.19°           -211.37°
+02            1.121e-01           6.310e-03             84.45°            -85.73°
+02            6.981e-02           3.930e-03            160.79°             -9.39°
+02            5.556e-02           3.127e-03            -79.83°           -250.01°
+03            3.100e-02           1.745e-03             12.22°           -157.96°
+03            3.112e-02           1.752e-03            117.37°            -52.81°
: 33.223681%(33.224455%)



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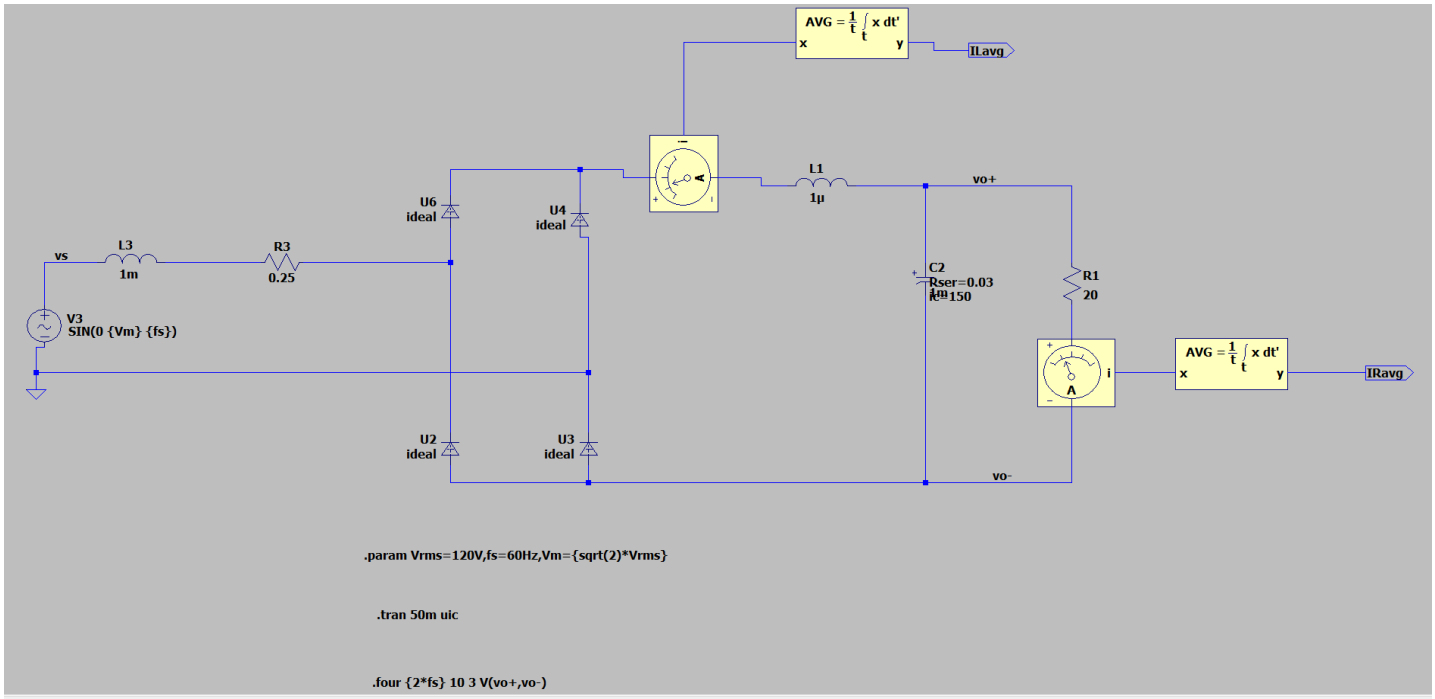
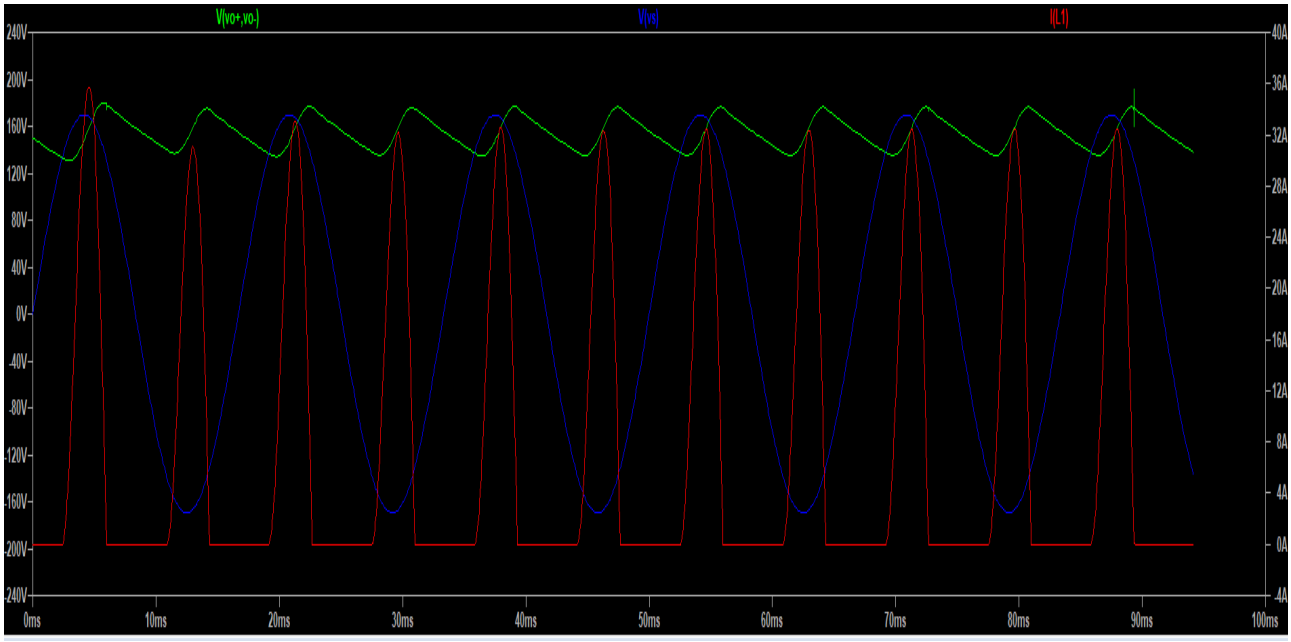
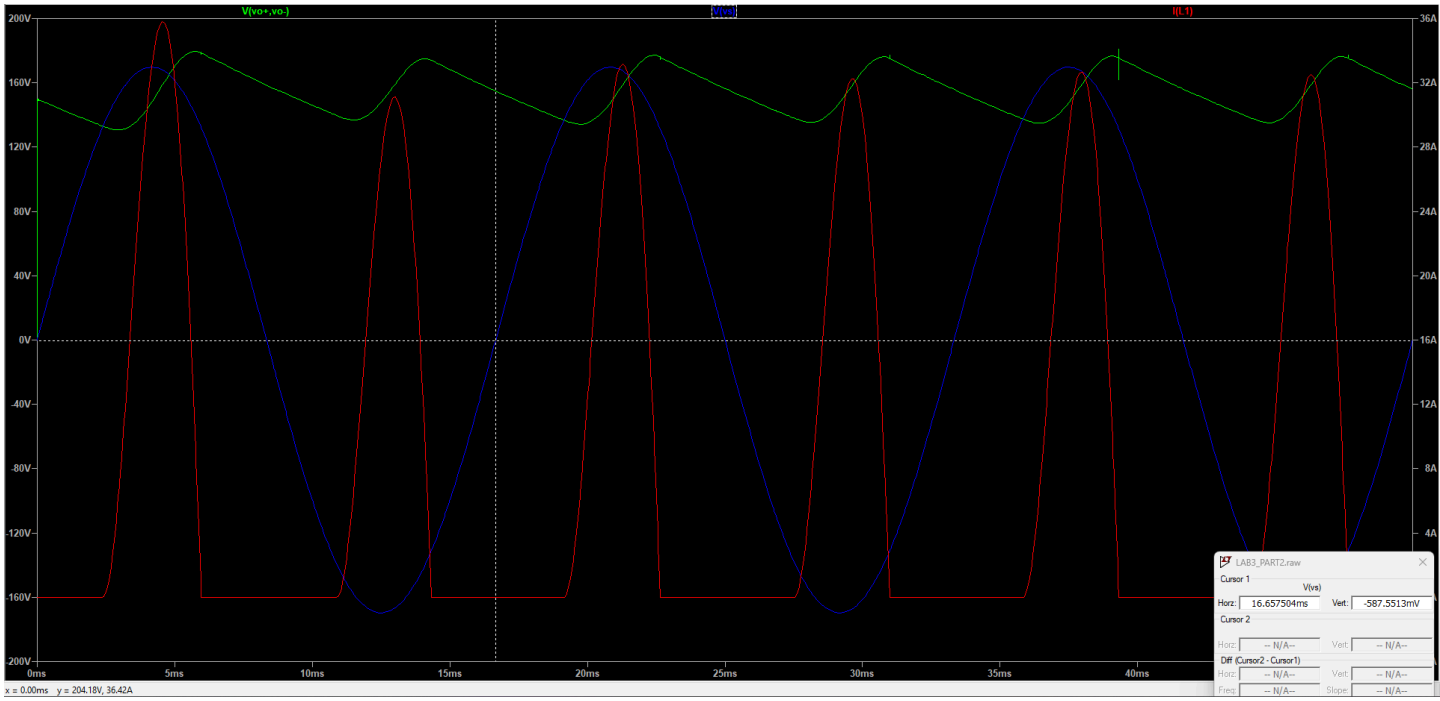
4)
The schematic:



The waveform V(vo+,vo-),V(vs), and I(L1)



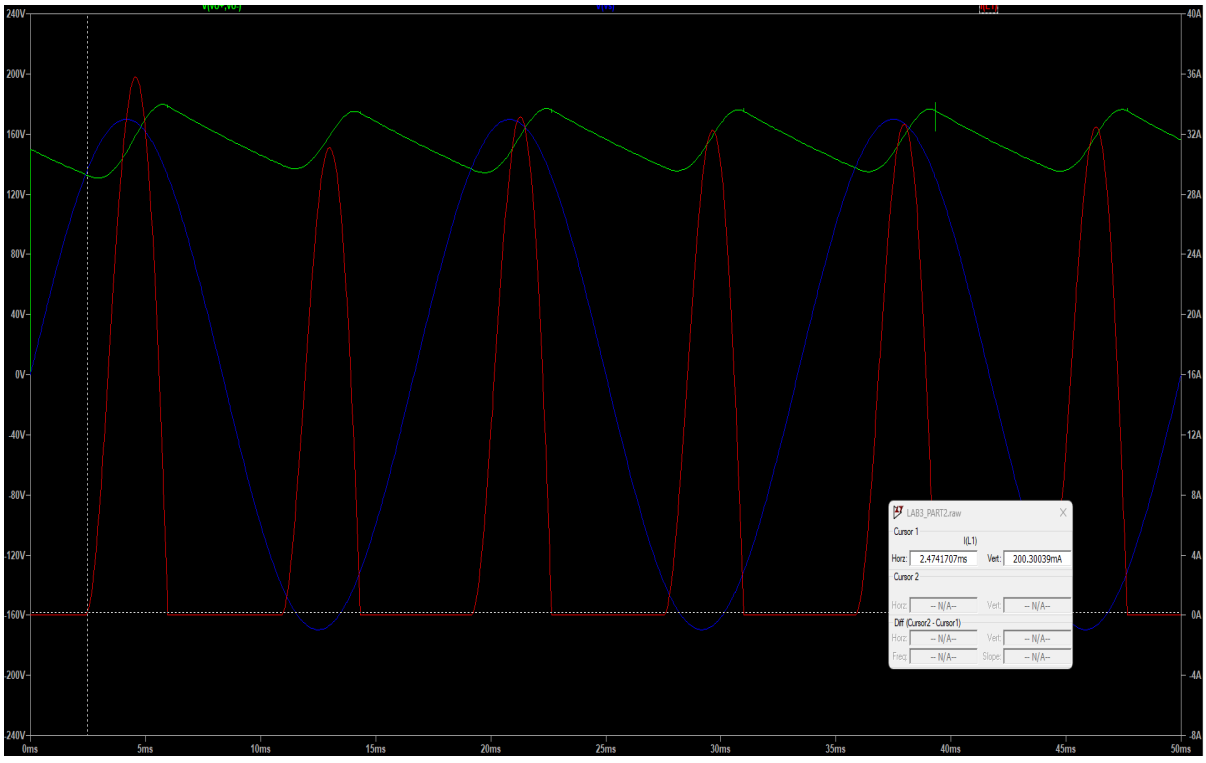
5) Based on the graph, the I(L1) is discontinuous:



Observing from the graph above , at **t= 16.65(s) -> VS=0(V)**

angle= wt= 2pi*60 * 16.65 = 1998pi

7) The time when I(L1) is about to turn on:

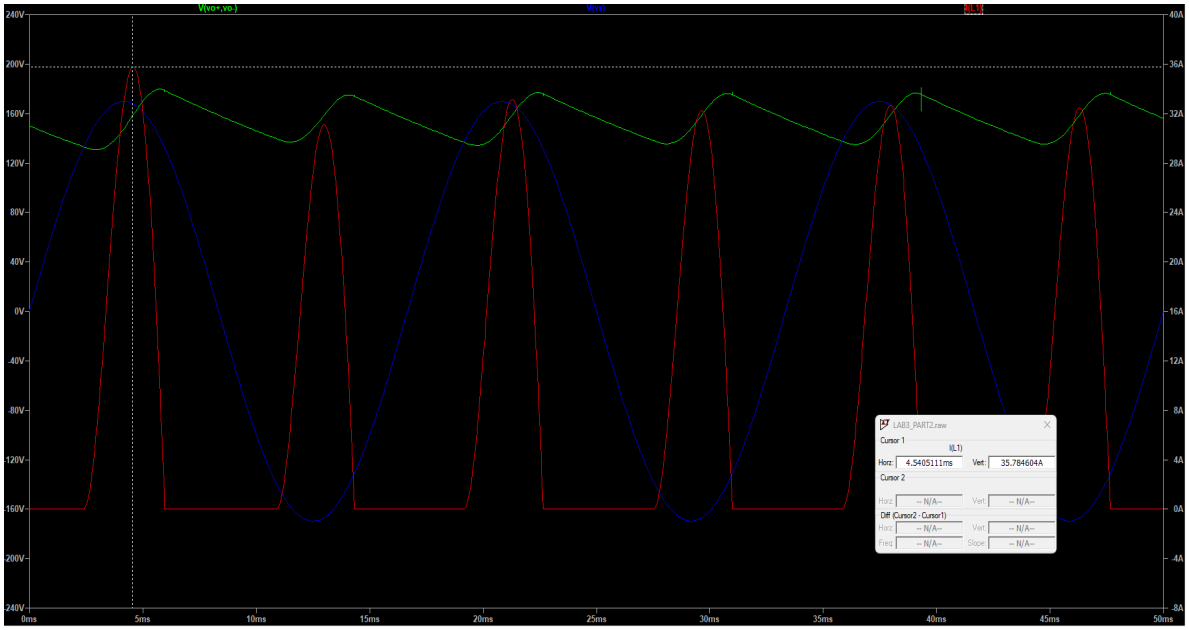


At tb= 2.474 or roughly 2.5(s):

theta(b)= wtb = 2pi*60 * 2.5 = 300pi = 942.48 degrees

The output voltage and source voltage values is around -150V

8) The time when I(L1) is at maximum peak:

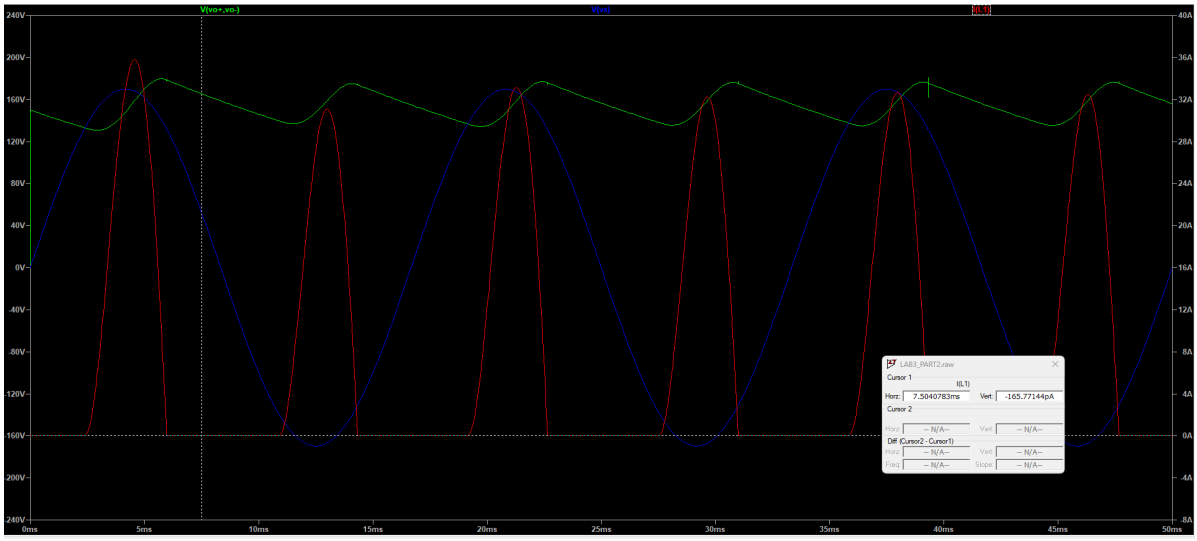


At tp= 4.5405 (s):

theta(p)= wtp= 2pi*60*4.5405 = 1711.72 degrees

The feature of output voltage at this angle is 200 V

9) The time it takes when I(L1) is at 0:



At tf= 7.504:

theta(f)(extinction angle)= wtf = 2pi*60 * 7.504 = 2828.94 degrees

The feature of output voltage at this angle is -160V

Practice Problem Encounters:

The common problem we encountered during this lab was mainly with the simulation. The simulations were quite weird on my partner's machine because sometimes my partner couldn't capture the data from SPICE LOG. He was only able to obtain the data once, but the rest of the time, he couldn't.

Conclusion:

The goal of this lab is to understand the full wave bridge rectifiers circuits in CCM and DCM. Based on that, we simulate the circuits on the LTSpice and observe the characteristics behavior of the full wave bridge rectifiers. In the first part of the lab, the objective is to obtain the plot between the relationship of voltages and currents in the full wave rectifiers CCM mode. In the second part of the lab, the objective is to observe the relationship of the waveform between the V(vo+,vo-), V(vs), and I(L1). The next task is determining the angle of current I(L1) when the current is turning on, minimum, and maximum when the steady-state is reached. Final part of this section is calculating the Fourier series.