IGEE 401 Lab 1 AC Controllers

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1.1 Objectives

The objective of this experiment is to get familiar with EMTP and MATLAB and to be able to obtain relevant plots. Additionally, the goal is to be able to analyze single-phase and three-phase thyristor-based AC controllers, feeding resistive, inductive, and resistive-inductive loads.

1.2 Preliminary Calculations

Question 1

a. $Q = \frac{V_S^2}{2\pi f L} = \frac{18.8k^2}{2\pi(60)(93.7m)} = 1.00 \times 10^7 \, VAr$

b. $Q = \frac{V_S^2(2\pi - 2\alpha + sin2\alpha)}{X_L \pi}$

c. The figure below shows the relation between reactive power and firing angles. Firing angle that achieves 75% of rated reactive power was obtained graphically. Based on the graph, angle is around 101.402°.

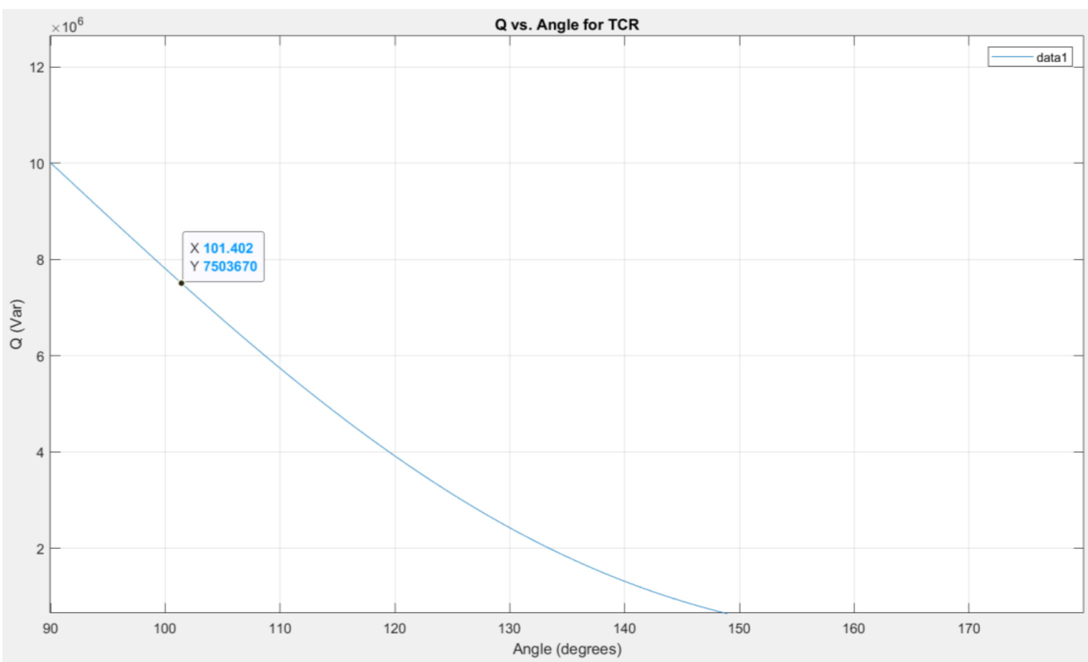

Figure 1 Reactive Power VS Firing angles

Question 2

a. Firing angle at 0 degrees achieves maximum absorbed power by the load. At firing angle of 0, thyristor is triggered immediately at the start of the half cycle. It is conducting for the longest duration possible. Thus, achieving maximum absorbed power.

b. The figure below shows the relationship between active power and firing angles.

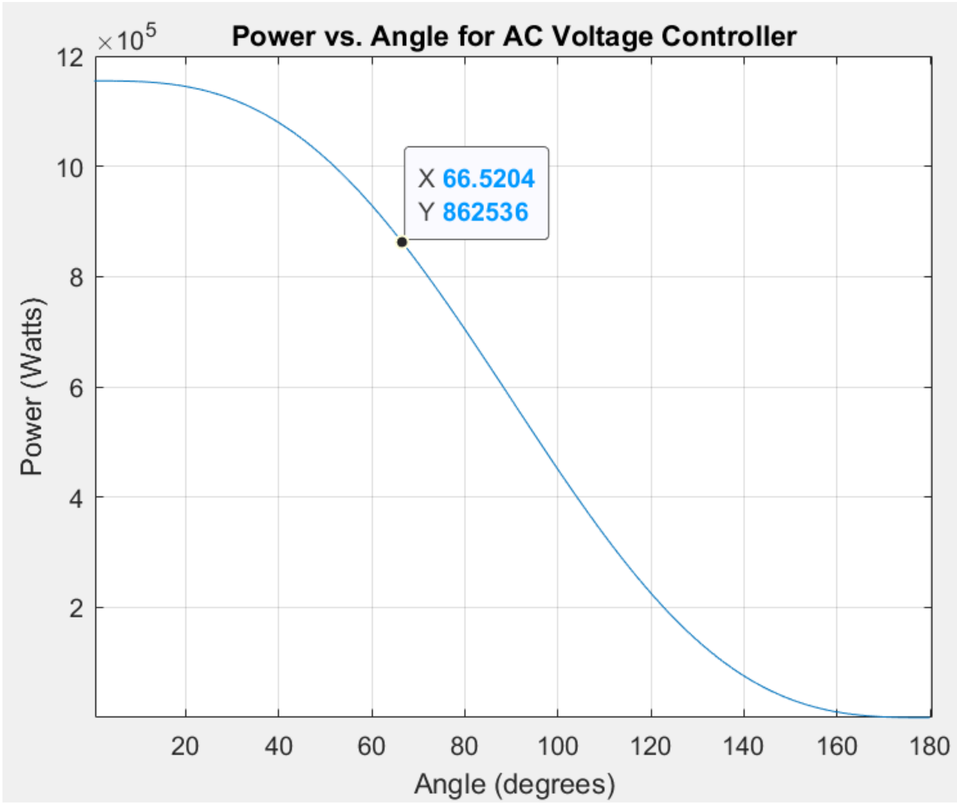

Figure 2 Active Power Vs Firing angles

c. The highest point is at 115030 W. Therefore, we need to locate the point at 75% of that value which is close to 86272.5 W. Firing angle that achieves 75% of rated reactive power was obtained graphically. Based on the graph, angle is around 66.5204°.

Question 3

$$V_p = \frac{V_L}{\sqrt{3}} = \frac{600}{\sqrt{3}} = 346.4\ V$$

$$\alpha\ = 90°\ =\ \pi/2$$

$$R = 0.25\ \Omega$$

$$V_m = \sqrt{2} * V_p = 489.90\ V$$

$$P = \frac{V_m^2}{4\pi R}\left(2\pi - 2\alpha + sin(2\alpha)\right) * 3 = 732\ kW$$

1.3 Experimental procedures and results

1.3.1 Single-Phase Thyristors AC Controller with RL and R Loads

1.3.1.1 RL-load

c. Input voltage at the AC controller, load current, and voltage and gate signal of the thyristors at a firing angle of 60 degrees and a current pulse of 9 degrees are shown in the figure below

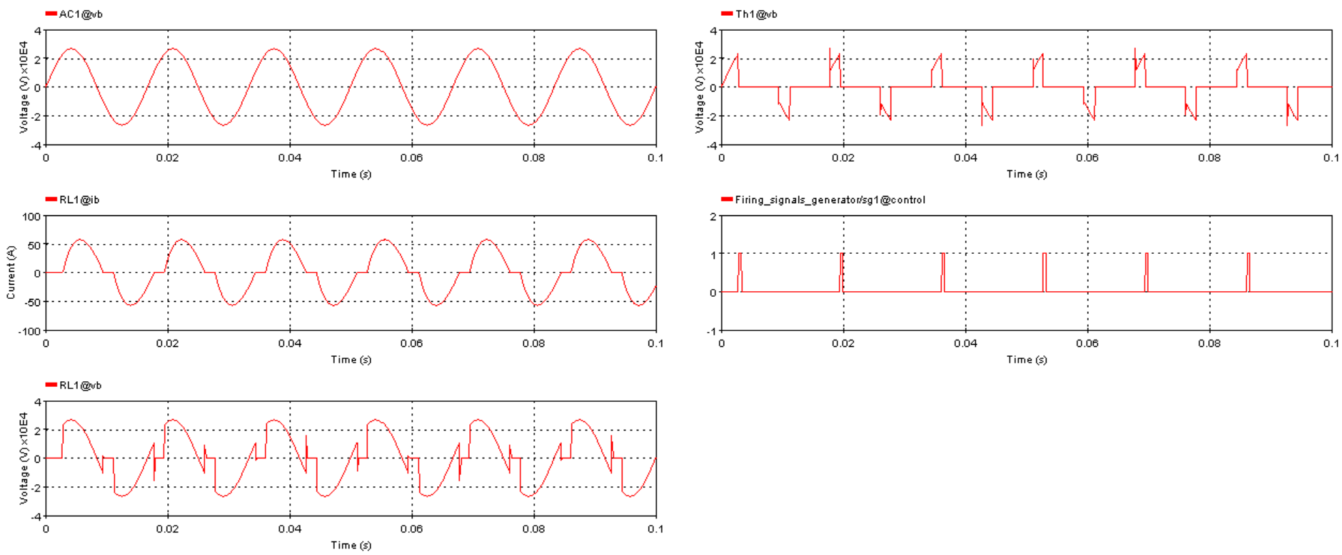

Figure 3 Waveform for input voltage, load current, and voltage and gate signal

d. The calculations for extinction angle for 60 degrees firing angle is shown below.

$$Extinction\ Angle\ \ 60° = Time\ \times 360\ \times 60\ =\ 0.0094309 * 60 * 360\ = 203.71°$$

$$Extinction\ Angle\ \ 10° = Time\ \times 360\ \times 60\ =\ 0.0094375 * 60 * 360\ = 203.85°$$

$$Extinction\ Angle\ \ 120° = Time\ \times 360\ \times 60\ =\ 0.009331 * 60 * 360\ = 201.55°$$

e. The harmonic spectrum of the load voltage and current waveforms are shown below.

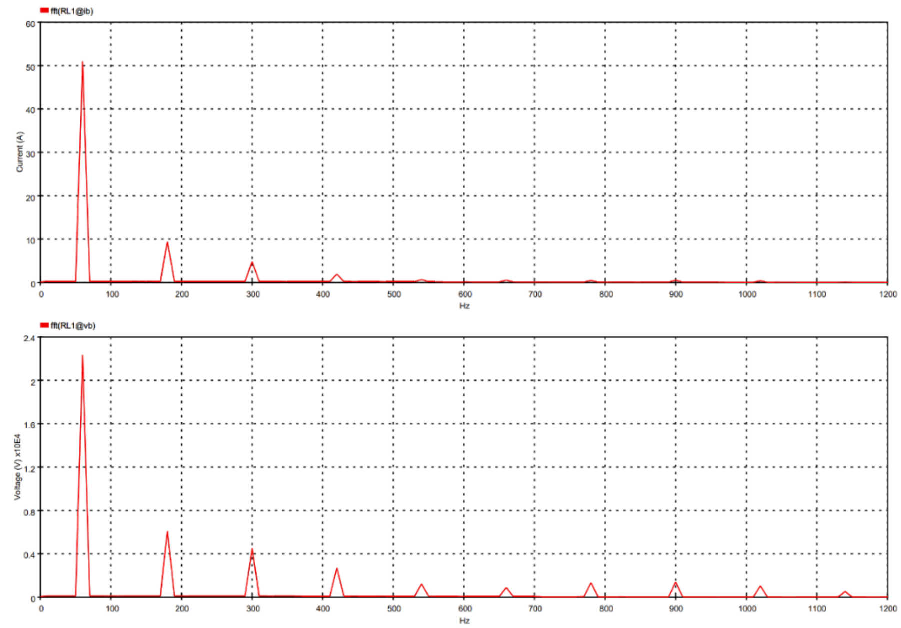

Figure 4 Load voltage and current spectrum for 60 degrees firing angle

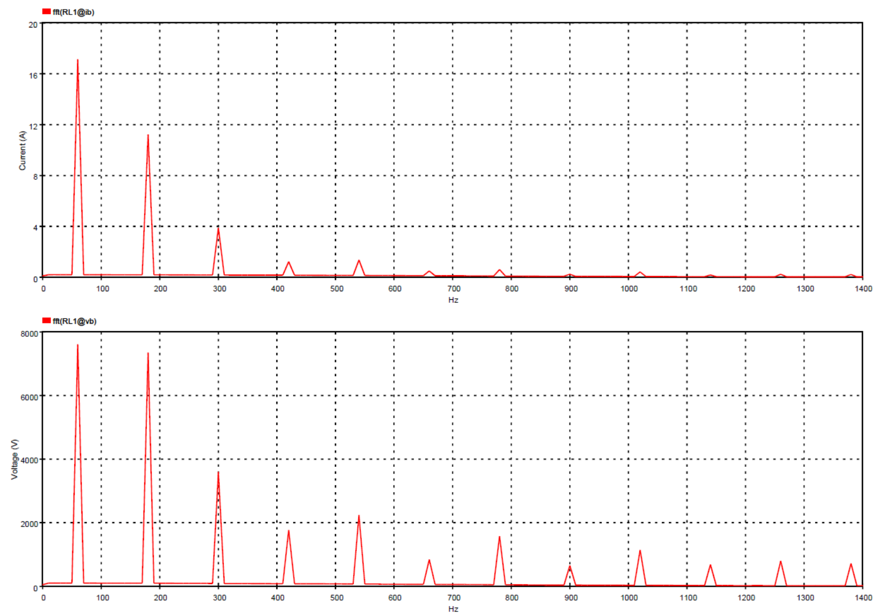

Figure 5 Load voltage and current spectrum for 120 degrees firing angle

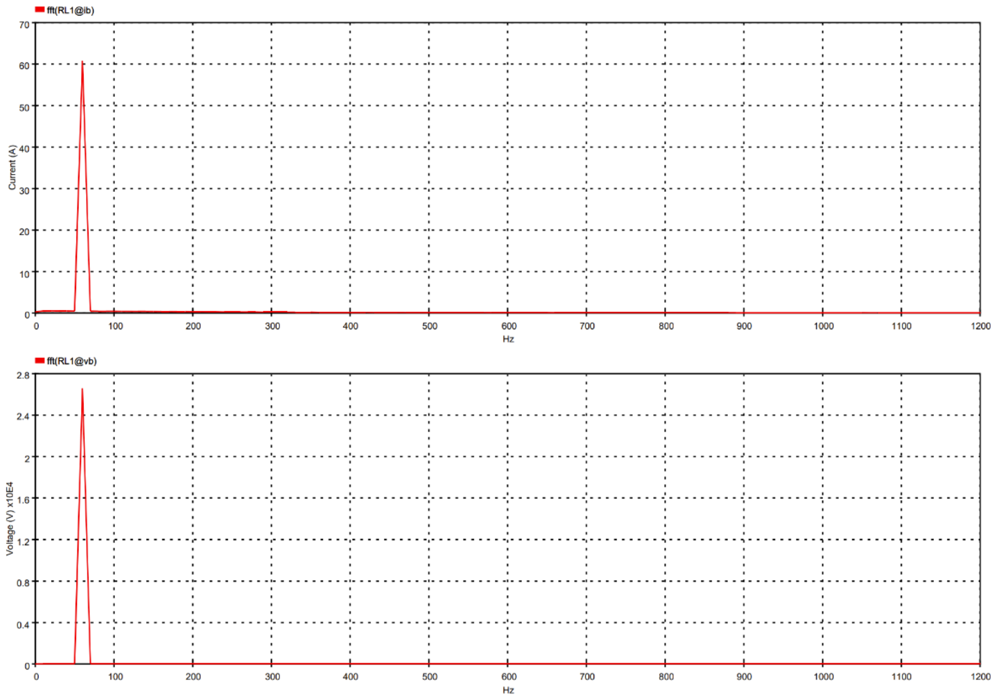

Figure 6 Load voltage and current spectrum for 10 degrees firing angle

f. Formulas used for the calculation are shown below.

$$Fundamental\ RMS\ Current\ I_{s1}: Obtained\ graphically\ on\ spectrum\ graph\ , 1st\ peak$$

$$Fundamental\ RMS\ Voltage\ V_{s1}: Obtained\ graphically\ on\ spectrum\ graph, 1st\ peak$$

$$Total\ RMS\ Current: I_s = \sqrt{I_{s1}^2 + I_{s2}^2 + \cdots + I_{sh}^2}$$

$$Distortion\ Current: I_{dis} = \sqrt{I_s^2 - I_{s1}^2}$$

$$Current\ THD: THD = 100\ \frac{I_{dis}}{I_{s1}}$$

$$Current\ Crest\ Factor: CF = \frac{i_{s,peak}}{I_s}$$

$$Voltage\ THD: THD = 100\frac{V_{dis}}{V_{s1}}$$

$$Active\ Power = V_{s1} \times I_{s1} \times cos\emptyset$$

$$Reactive\ Power = V_{s1} \times I_{s1} \times sin\emptyset$$

$$Dispalcement\ Power\ Factor\ DPF = cos\emptyset$$

$$Distortion\ Power\ Factor = \frac{1}{\sqrt{1 + THD^2}}$$

$$Power\ Factor: PF = \frac{1}{\sqrt{1 + THD^2}} \times DPF$$

Parameters	Firing Angle ∝ (deg.)		
	10	60	120
Fundamental RMS Current (A)	42.996	50.959	12.113
Total RMS Current (A)	42.996	36.907	14.809
Distortion Current (A)	0	7.9801	8.5194
Current THD(%)	1.11	21.1418	70.2012
Current Crest Factor	1	0.9763	0.8180
Voltage THD(%)	0.21	36.0758	113.882
Active Power (W)	742262	522787	60076
Fundamentals Reactive Power (Var)	319760	224391	25290
Displacement Power Factor	0.9184	0.9189	0.9217
Distortion Power Factor	1	0.8972	0.8180
Power Factor	0.9184	0.8246	0.7539
Extinction Angle	203.85	203.71	201.55
Fundamental RMS Load Voltage (V)	18797.44	15788.35	5381.04

Table 1 Single-phase AC-controller characteristics (RL-load)

1.3.1.2 Purely resistive load(R-load)

b. By updating and plotting the provided code, we found the firing angle that results in 50% of rated power to be around 89.496 degrees.

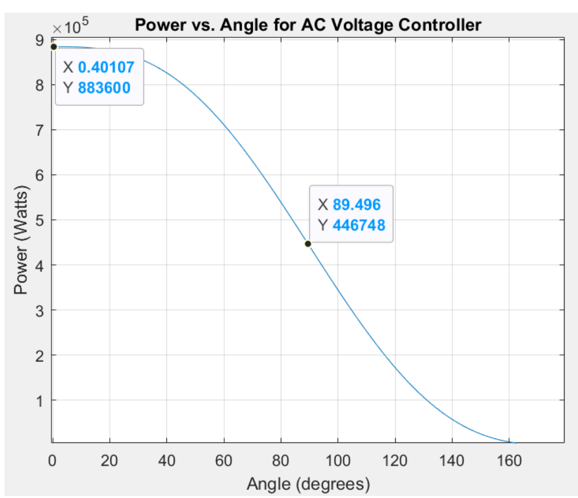

Figure 7 Power Vs. Angle for AC Voltage Controller

d. Input voltage at the AC controller, load current and voltage and gate signal of the thyristor are shown below.

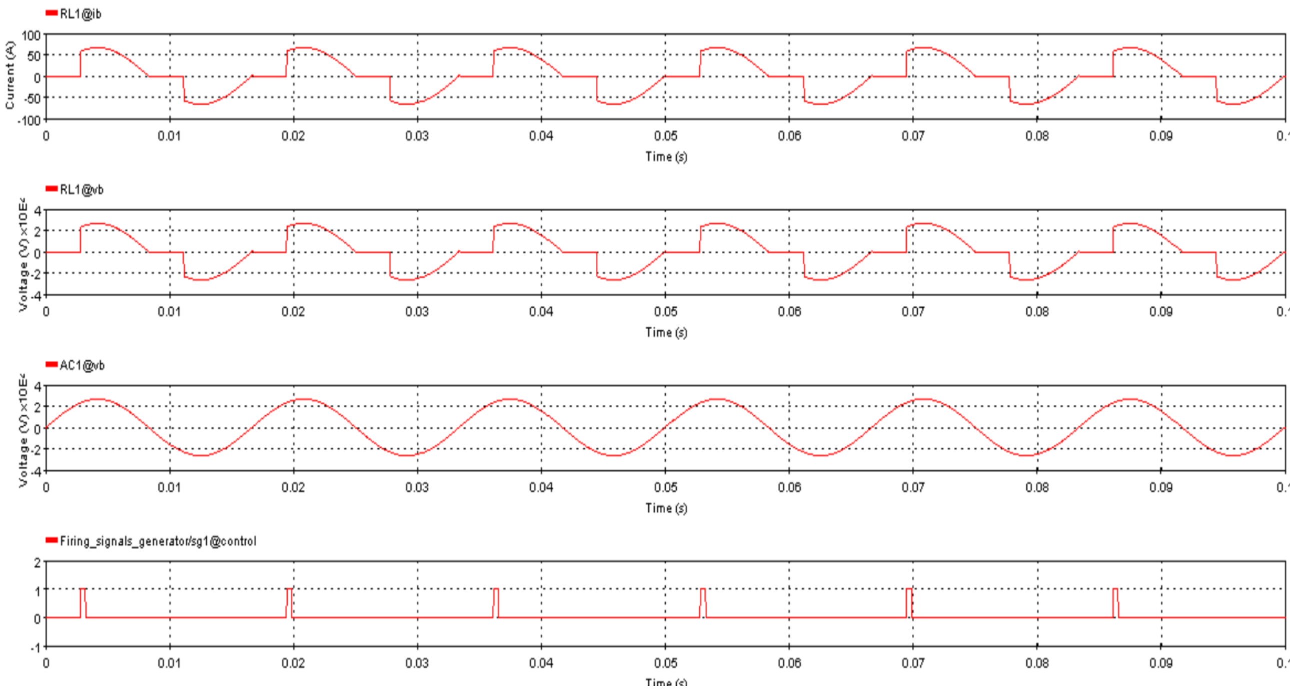

Figure 8 Waveform of input voltage, load current and voltage, and thyristor gate signal

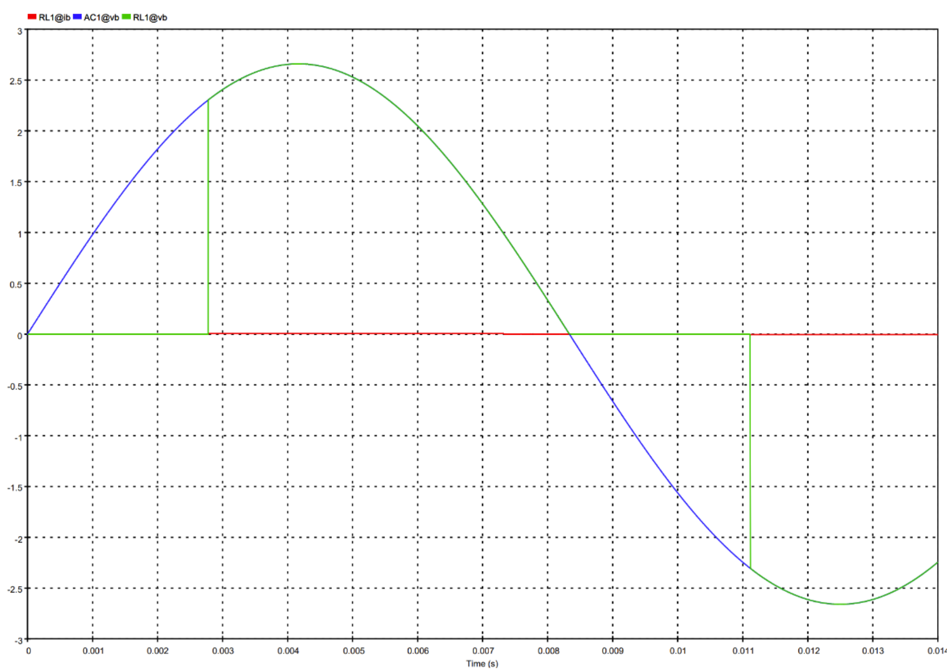

Figure 9 Superimposed graph of input voltage, load current and load voltage

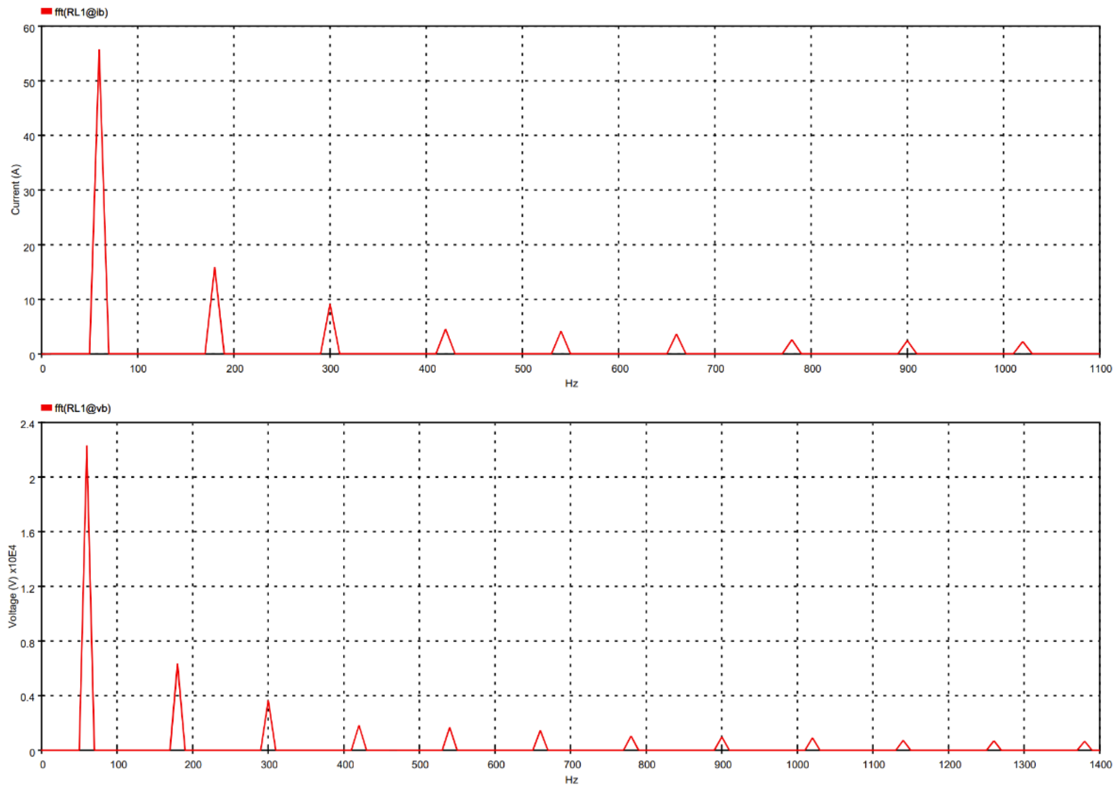

Figure 10 Harmonic Spectrum of load current and voltage

The following parameters are calculated using the same equation mentioned in 1.3.1.1.

Parameters	Firing Angle of 60
Fundamental RMS Current (A)	39.4352
Total RMS Current (A)	41.8998
Distortion Current (A)	14.15836
Current THD(%)	35.90
Current Crest Factor	0.9412
Voltage THD(%)	34.70
Active Power (W)	710676
Fundamentals Reactive Power (Var)	0
Displacement Power Factor	1
Distortion Power Factor	0.9412
Power Factor	0.9412
Extinction Angle	180
Fundamental RMS Load Voltage (V)	15774.13807

Table 2 Single-phase AC controller characteristics (R-load)

1.3.1.3 Purely inductive load(L-load)

b. Updated and plotted the waveform using the provided code. Firing angle that results in 50% of rated power is found to be 113.778 degrees. Similar methodology was used to find firing angle that results in 75% of rated power which is 101.402 degrees.

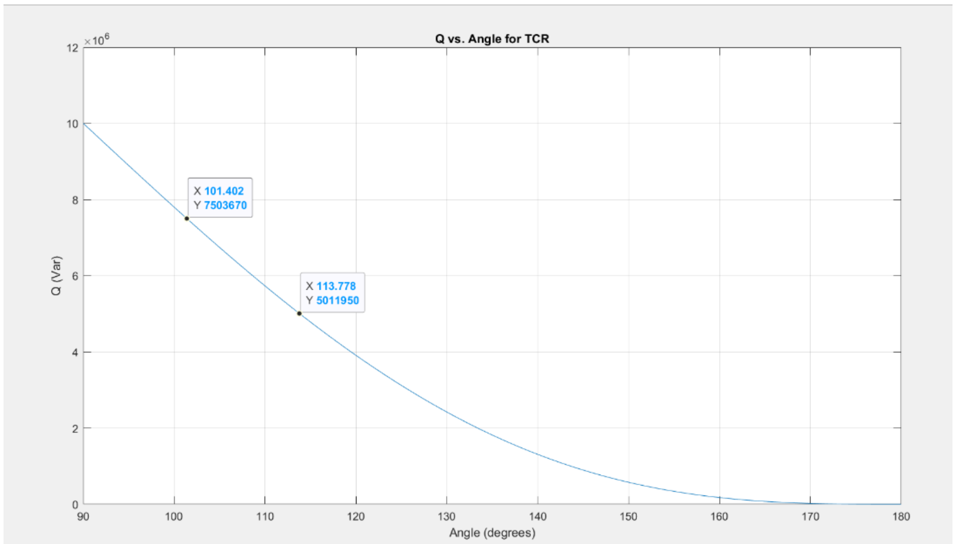

Figure 11 Q Vs. Angle for TCR

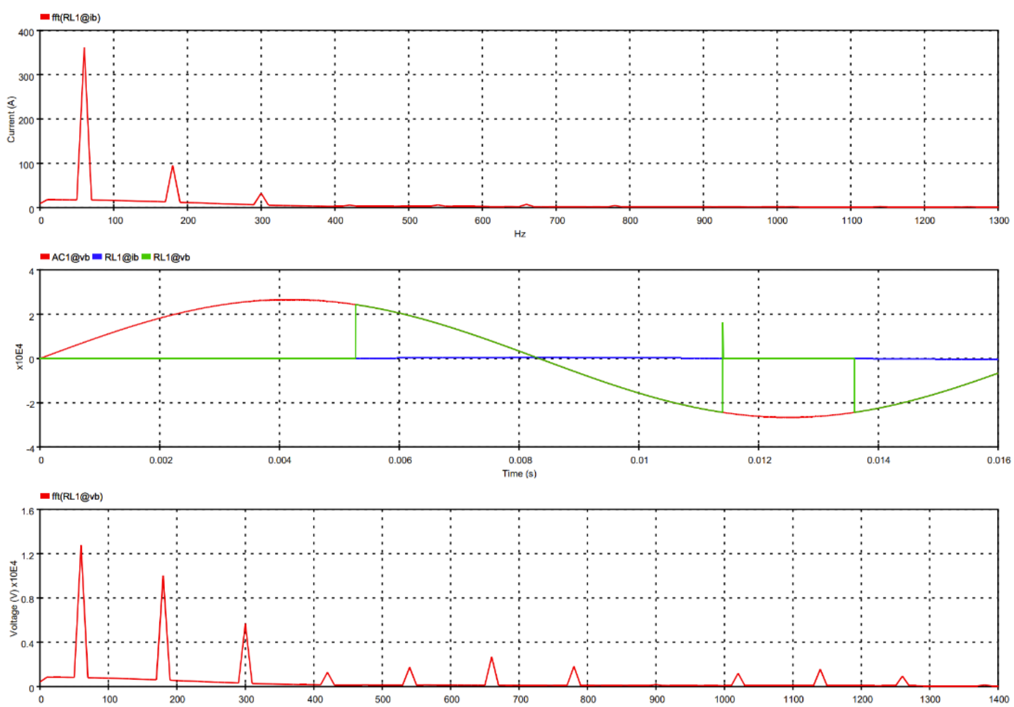

Figure 12 Waveforms for 50% Rated Power

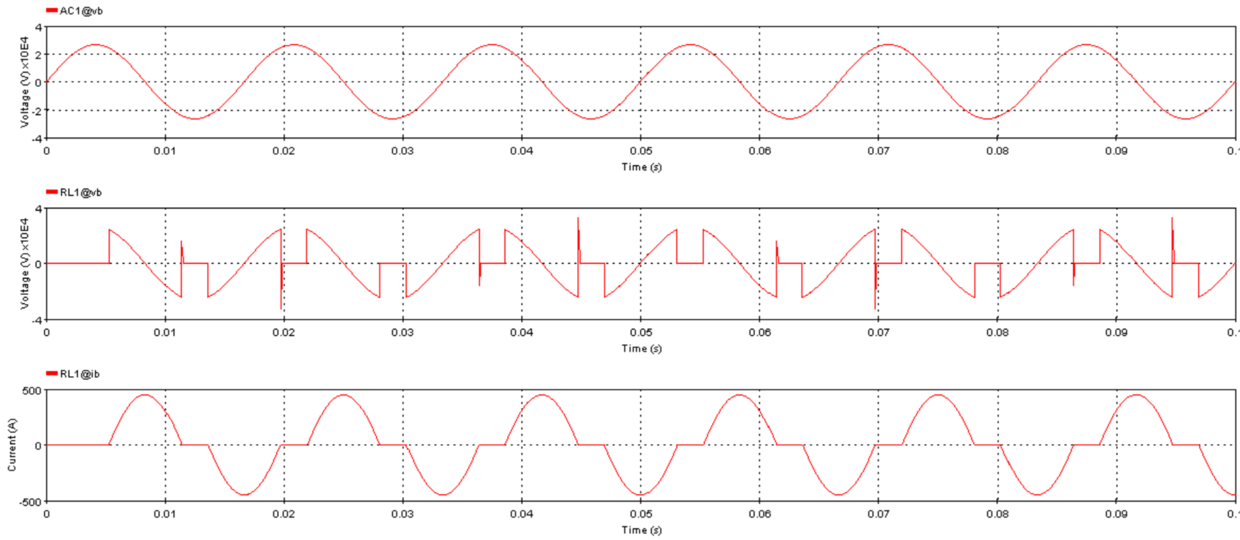

Figure 13 Waveforms for 50% Rated Power

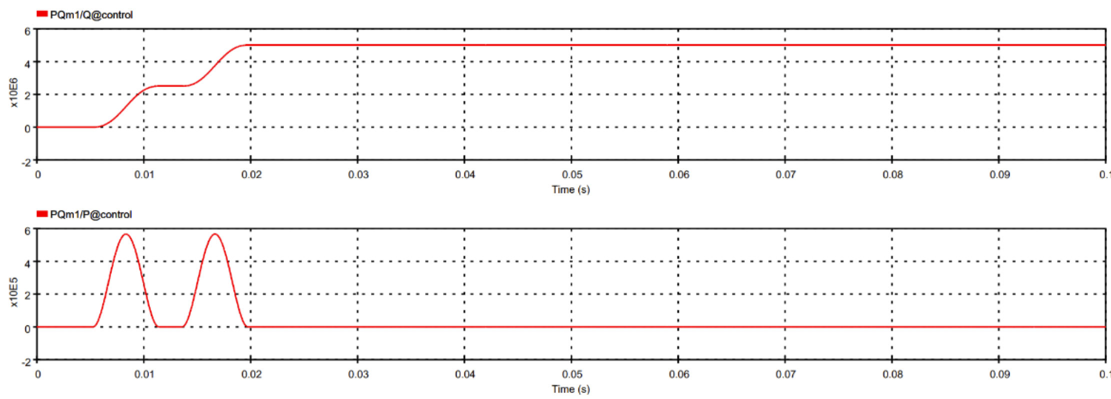

Figure 14 Active and Reactive power for 50% rated

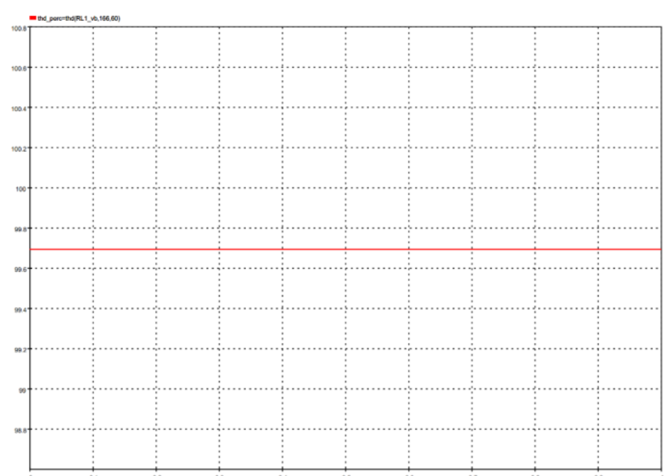

Figure 15 Voltage THD for 50% rated

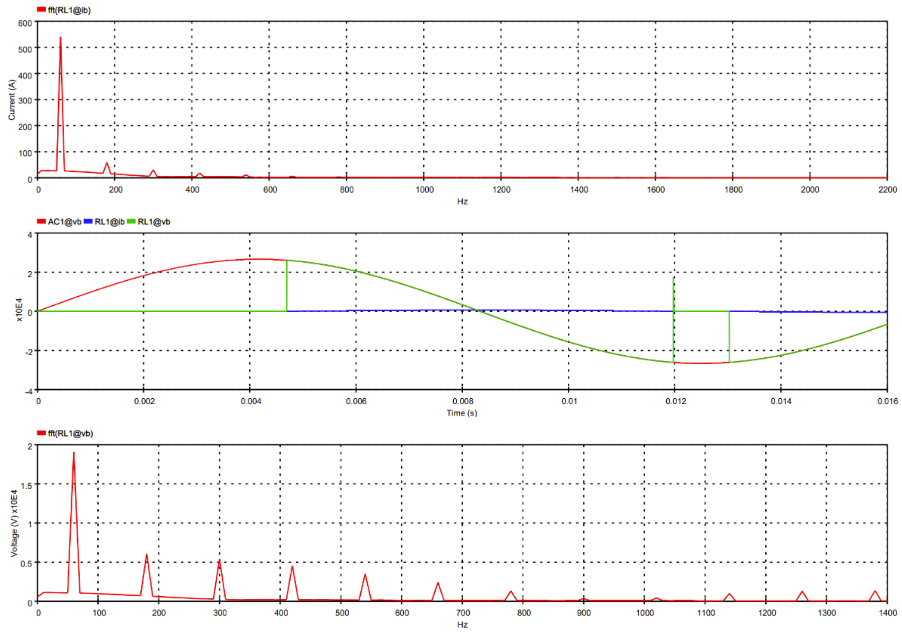

Figure 16 Waveforms for 75 % rated power

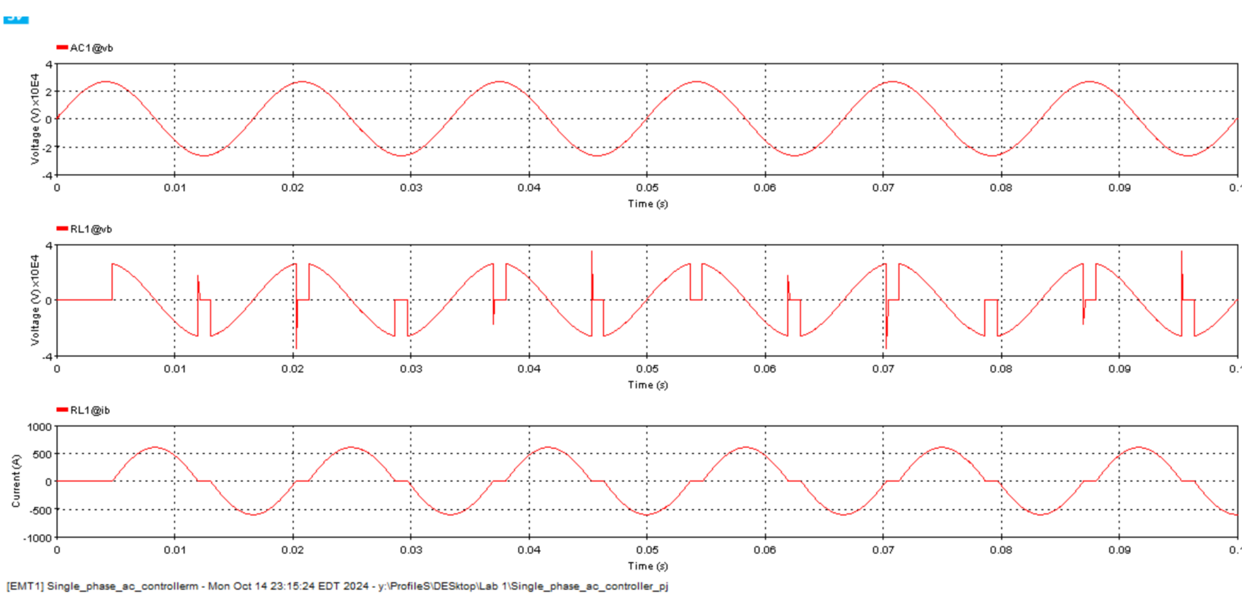

Figure 17 Waveforms for 75% Rated Power

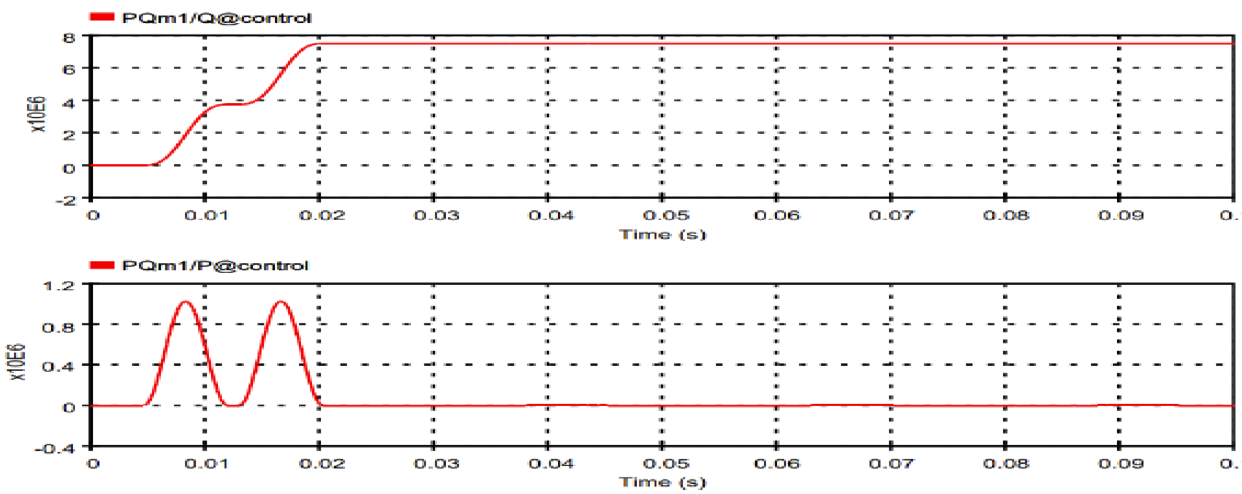

Figure 18 Active and reactive power for 75 % rated power

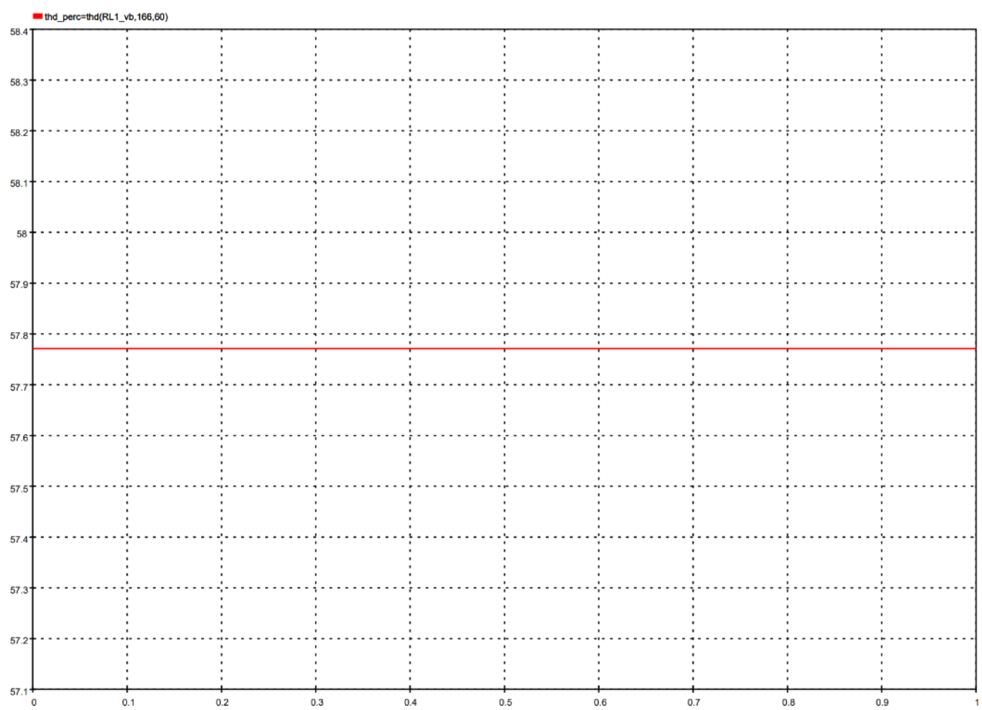

Figure 19 Voltage THD for 75% rated

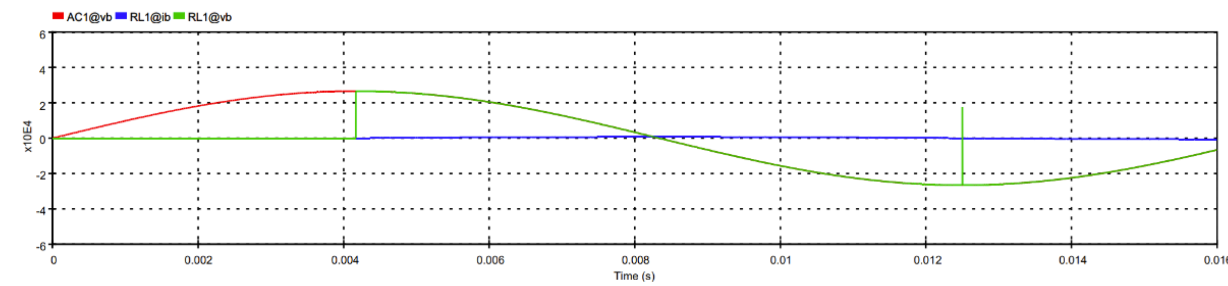

Figure 20 Superimposed Waveform for 100% Rated

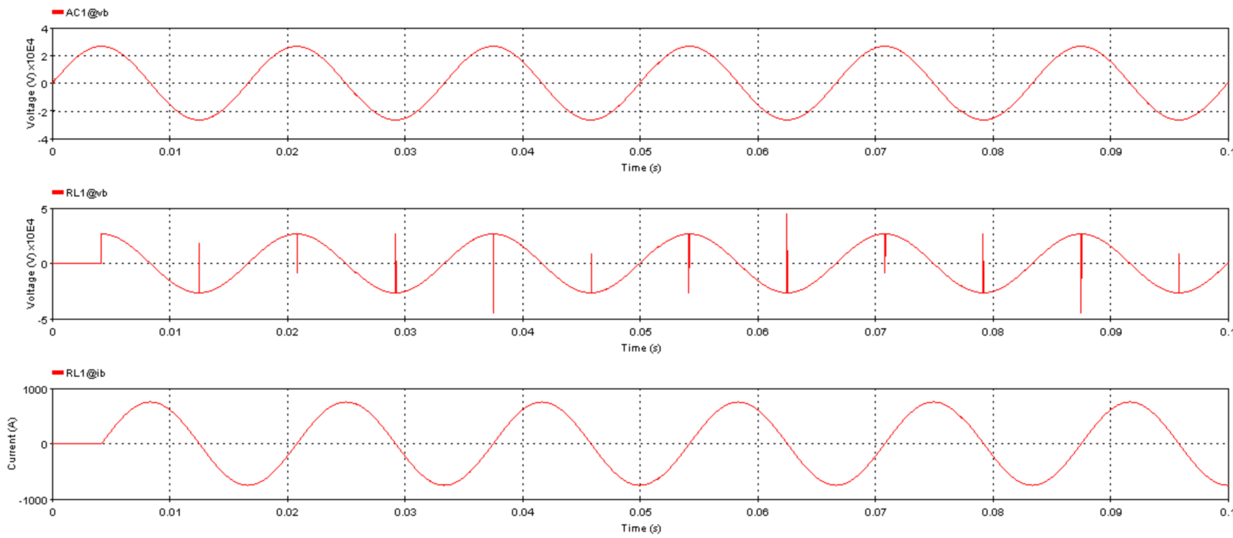

Figure 21 Waveforms for 100% Rated Power

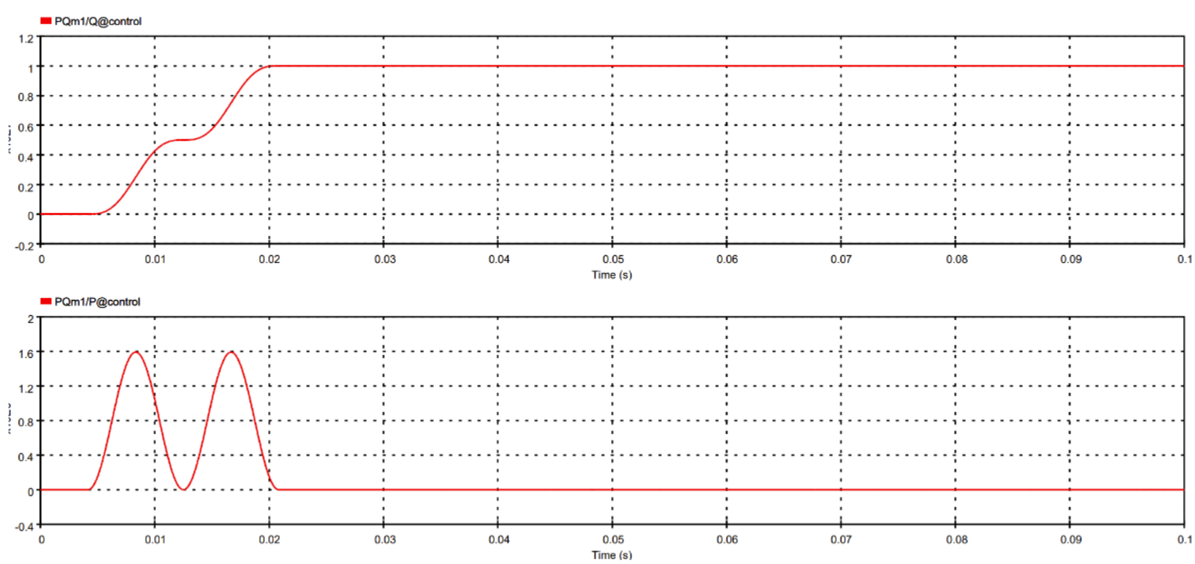

Figure 22 Active and Reactive Power for 100% Rated

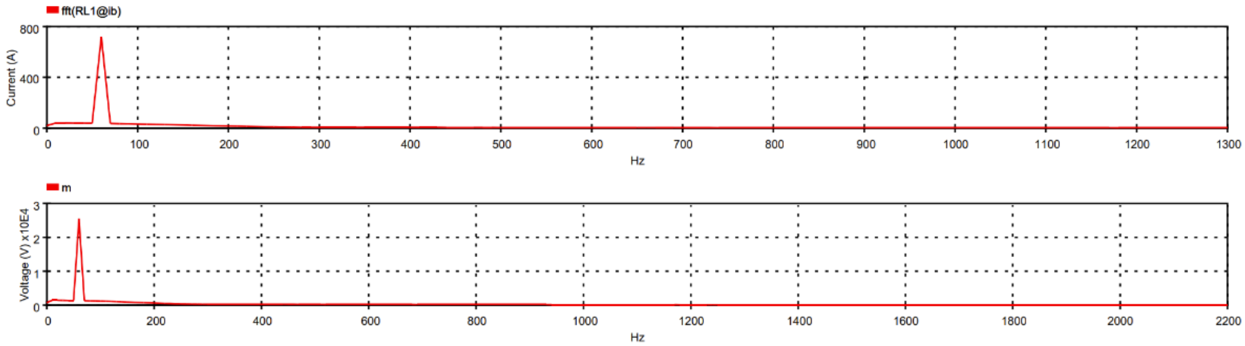

Figure 23 Harmonic Spectrum for 100% Rated

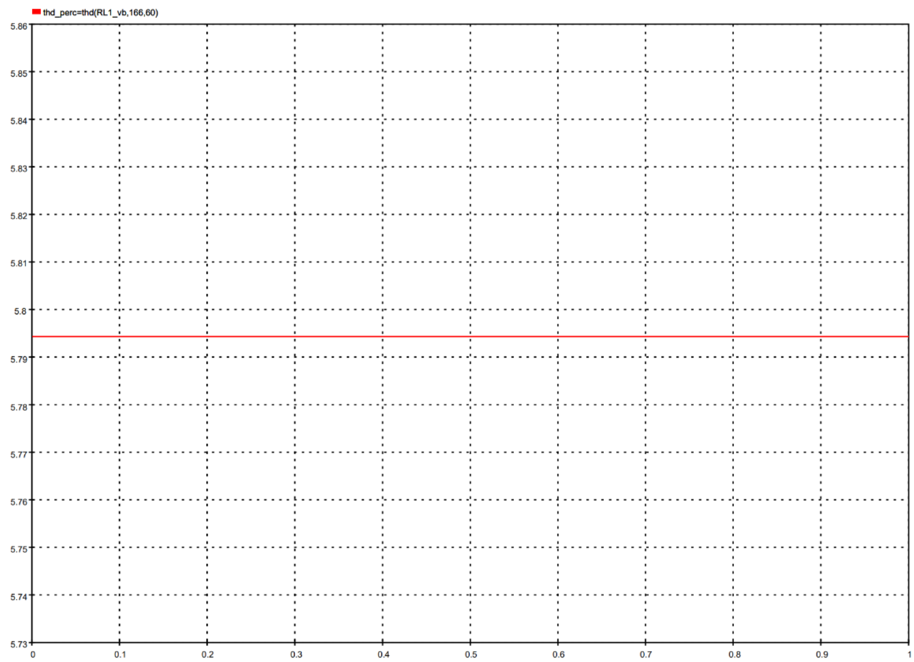

Figure 24 Voltage THD for 100% Rated

Experimental active and reactive power are found from the waveform.

Theoretical Reactive power is found from the MATLAB simulation.

Current extinction angle is found from recording the x value of the extinction point on the waveform and times it by 360 and 60.

Conduction angle is calculated by the difference of extinction and firing angle.

Voltage THD is directly measured from the waveform.

The power factor appeared to be 0 for all of them since no active power component is present.

Parameters	Reactive Power, Q(% of rated value)		
	100%	75%	50%
Active Power P (W)	0	0	0.2107
Reactive Power Q (Var)	10×10^6	7501940	5010480
Theoretical Reactive Power (Var)	10×10^6	7503670	5011950
Current Extinction angle	270	258.5952	246.5424
Conduction angle	179.982	157.1932	132.80328
Voltage THD(%)	5.794	57.77	99.69
Power Factor	0	0	0

Table 3 Single-phase AC-controller characteristic (L-load)

1.3.2 Three-Phase AC Controller for Industrial Heating System

e. The line-to-neutral voltage of the phase-A of the voltage source, line current in phase-A, current in neutral return wire are plotted and shown in the figure below.

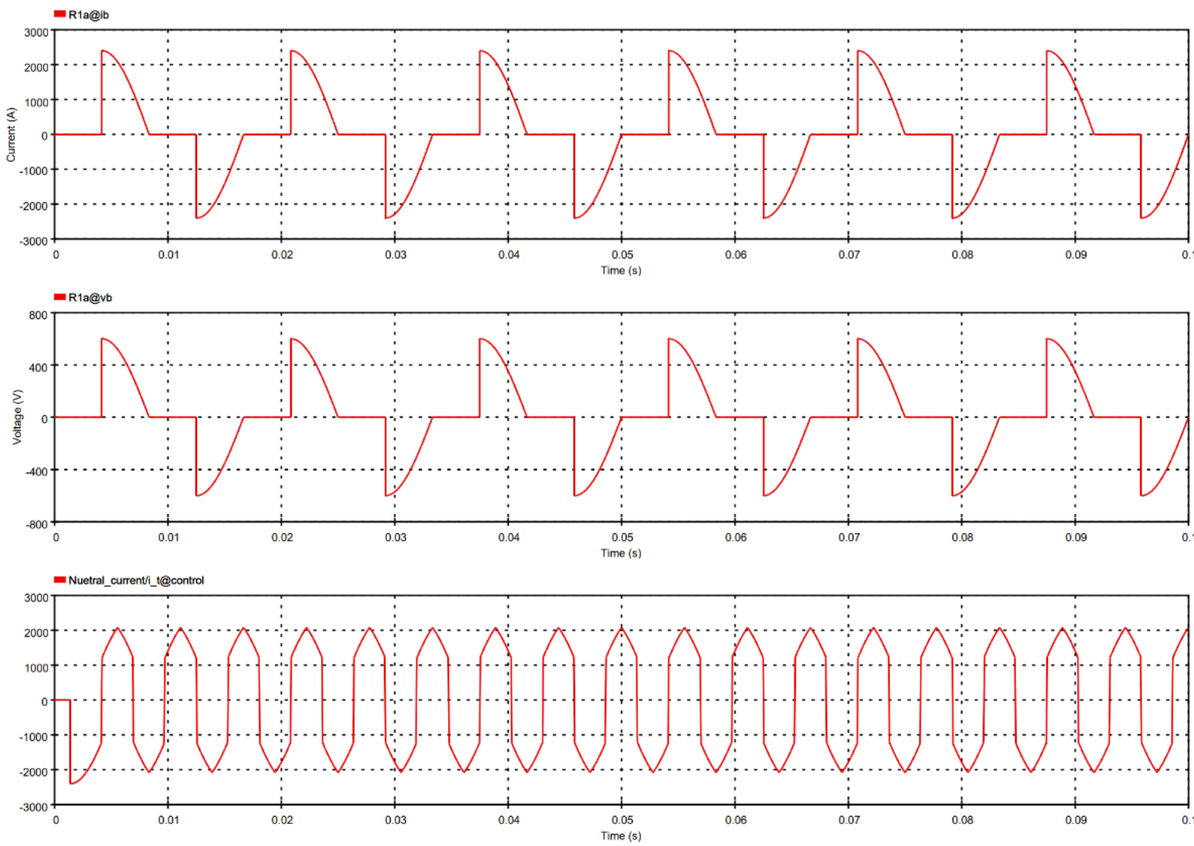

Figure 25 Three-phase thyristor-based AC controller with neutral wire waveforms

f. The harmonic spectrum of phase-A current and neutral wire current are shown below.

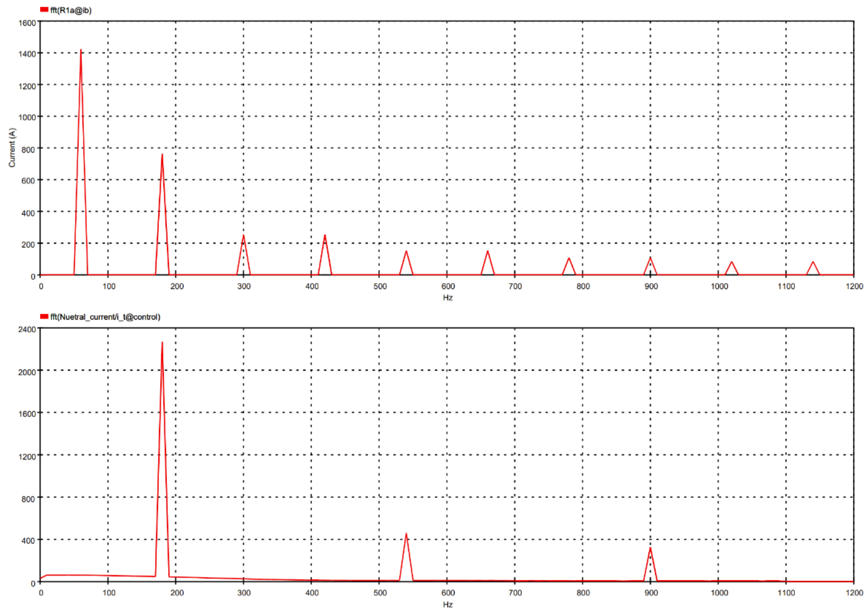

Figure 26 Harmonic Spectrums

h. With the removal of neutral wire, the line-to-neutral voltage of the phase-A of the voltage source, line current in phase-A, current in neutral return wire are plotted and shown in the figure below.

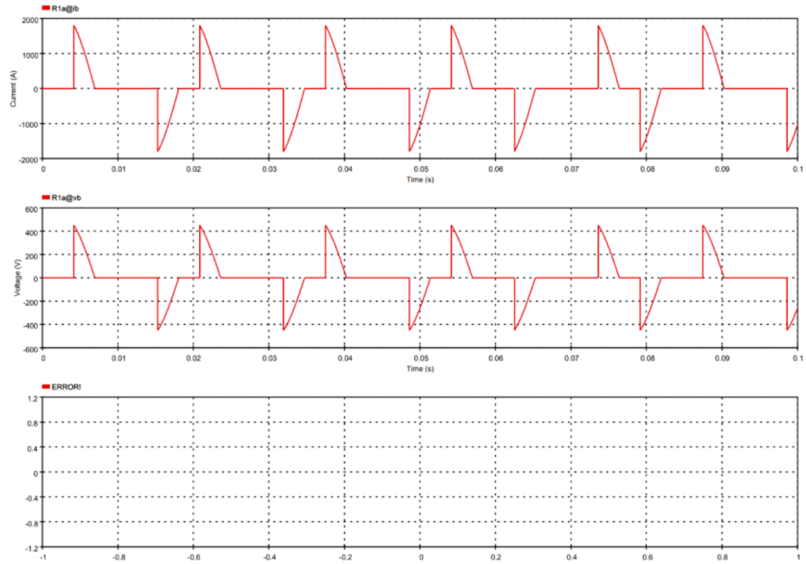

Figure 27 Three-phase thyristor-based AC controller without neutral wire waveforms

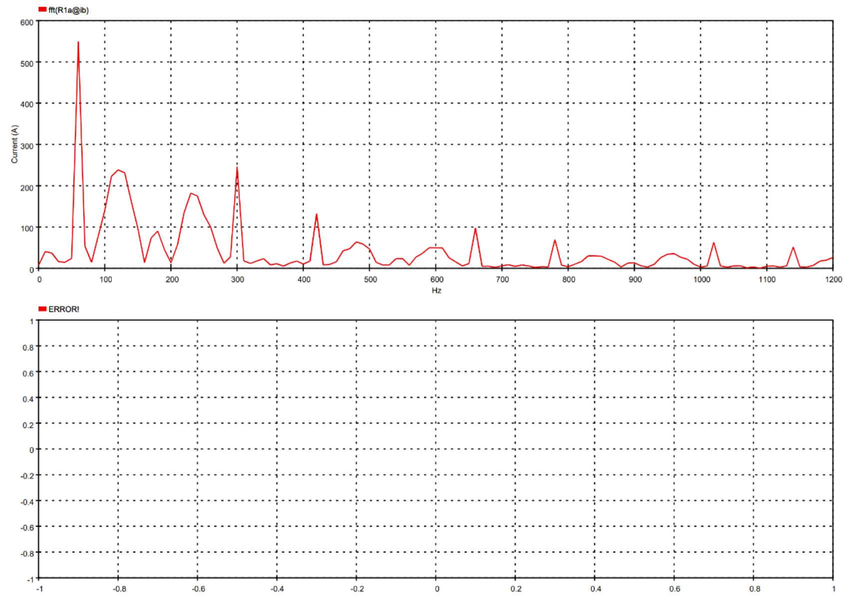

Figure 28 Harmonic Spectrum

The THD values are directly measured from the EMTP.

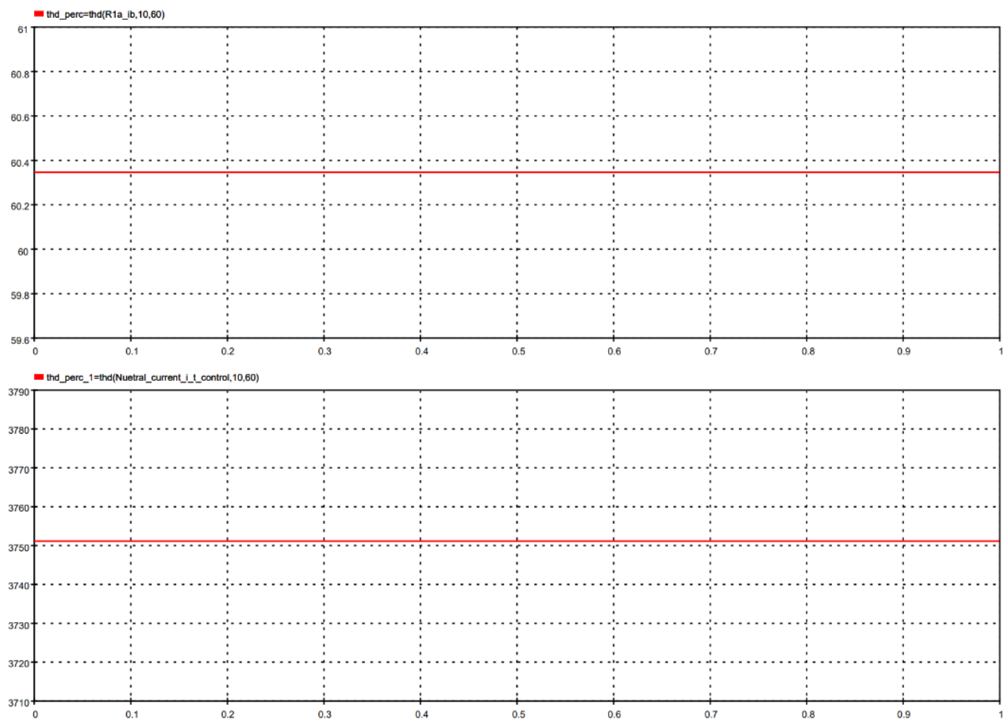

Figure 29 THD values with neutral wires

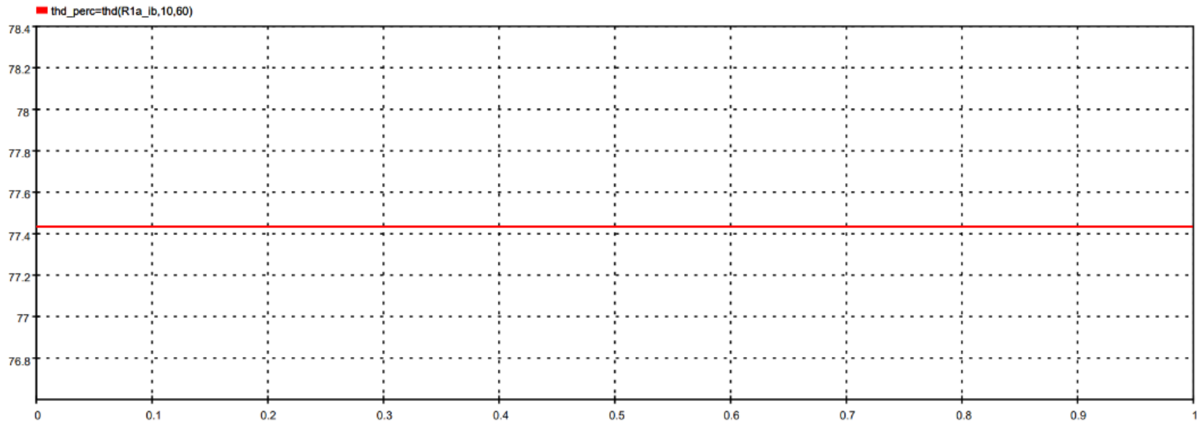

Figure 30 THD Values without neutral

Neutral point	Current THD (%)
Phase-A line current with neutral	60.34
Phase-A line current without neutral	77.4326
Neutral current	3751.14

Table 4 Total Harmonic Distortion of the line and neutral currents

1.4 Questions and discussions

1). **Why the load current presents a smaller THD than the load voltage in a thyristor based AC controller? (Refer to Section 2.4.1.1.f in the lab manual)**

Inductor resists the sudden changes in current. When the thyristor switches on and off, voltage waveform has sharp transitions with high frequency harmonics, but the inductance opposes these rapid changes by gradually decaying the current resulting in current waveform changes more slowly and smoothly. Inductor stores energy when current flows them. When the thyristor cuts off the voltage, the inductor releases the stored energy, ensuring current continues to flow for a brief period. This prevents abrupt changes in the waveform. Hence, the current waveform has a lower THD.

2). Why is there reactive power in the input (grid) side of the AC controller supplying a resistive load? (Refer to Table 1.2 in the lab manual)

The reactive power in the grid side is measured to be 211037 var. This happens due to the non-linear operation of the thyristor and its phase control mechanism. Thyristor turns on at the firing angle which delays the conduction of current and its voltage. It can introduce the phase difference lead to appearance of reactive power. The chopping of the voltage waveform results in a non-sinusoidal waveform. It creates harmonics that can cause phase shifts, further contributing to the reactive power.

3). What is the effect of varying the firing angle on the fundamental component of the current waveform and on the reactive power absorbed by the TCR? Are the variations linear? (Refer to Table 1.3 in the lab manual)

By increasing the firing angle, the reactive power absorbed decreased in a non-linear manner. As the firing angle increases, the effective reactance increases. Since the reactive power is inversely proportional to the reactance, the reactive power decreases. The firing angle determines the point in the AC cycle when the thyristor turns on. At a firing angle of 90, the thyristor turns on when the voltage is at its peak, allowing current to flow for nearly the entire half cycle. Thus, the current waveform is smoother and more sinusoidal. As firing angle increases, the thyristor turns on later in the AC cycle, shortening the time current can flow, leading to a decrease in conduction period. Therefore, the current waveform is more distorted and chopped.

4). Knowing that the AC controller forms a balanced three phase system, why is the neutral wire non-zero? (Refer to Section 2.4.2.h in the lab manual)

Neutral wires have triplen harmonic waves (multiples of the 3^{rd} harmonics). In a three-phase connected system, the triplen harmonics are in phase with each other. These harmonics flow through the neutral wire and do not cancel out. They sum constructively in the neutral causing a non-zero neutral current.

1.5 conclusions

During this lab, the team analyzed the performance of a phase-controlled thyristor AC controller with different types of loads, including RL, R, and L loads. The effects of firing angle on the current waveform, reactive power, and Total Harmonic Distortion (THD) were thoroughly investigated. For each load type, varying the firing angle demonstrated its impact on the conduction period, resulting in non-linear variations in the current waveform and power absorption. The team also explored a three-phase AC controller for an industrial heating system, noting how triplen harmonics in the neutral wire contribute to non-zero neutral current, even under balanced conditions. Overall, the experiments highlighted the significance of harmonic distortion and reactive power in thyristor-based AC systems.