SCHOOL OF ENGINEERING

ELECTRICAL AND COMPUTER SYSTEMS ENGINEERING

LABORATORY REPORT MARKING RUBRIC

ECE3051: ELECTRICAL ENERGY SYSTEMS

Experiment Number: 1

Title of Lab Sheet: SINGLE-PHASE AC NETWORKS

Group Number: 8

No.	Student ID	Name of Group Members	Total Marks
1	30720230	Loh Jia Quan	100/100
2	32194471	Tan Jin Chun	100/100
3	31106889	Agill Kumar Saravanan	100/100
4	30719305	Huan Meng Hui	100/100
5	32259417	Chong Yen Juin	100/100

MARKS BREAKDOWN

Section	Total Score	Actual Marks	Scoring Band	Criteria	Comment
Results	40		30-40	Clear and completely labelled figures of the experiment/simulation results with justifications and tables. A detailed caption is provided for each figure with an in-text figure reference. The x-axis and y-axis are labelled with the unit in the bracket. The legend is provided whenever it is deemed to be required. If there is more than one line, the lines should be clearly distinguishable with the visible difference such as dotted line, dashed line and solid line, even in black and white.	40
			20-30	Some of the figures of the experiment/simulation setup are not clear, do not have any labelling/ caption/ in-text caption reference/ distinguishable multiple lines and are blurry. The table and justification have mistakes or errors.	
			0-20	Insufficient amounts of figures and labelling of the experiment/simulation layout setup, which is not correct and/or unclear. The table is not filled.	
Discussion	40		30-40	Complete data collection and presentation using tables/figures/ graphs with appropriate labels. Discussion of the results with prudent judgment. Have a comparison of the measured results with theoretical values and in-text citations from the peer-reviewed references. The comprehensive comparison, evaluation and justification of the results are given with clear explanation to demonstrate the understanding of the laboratory.	40
			20-30	The discussion shows little understanding of what the experiment/simulation is all about. Brief comparison, evaluation and justification of the results, with unclear/ incorrect explanation on the theoretical and experimental/ simulation results.	
			0-20	Only restatement of the results without commenting on the expected key points. Incorrect judgment/ arguments were used. No comparison, evaluation and justification of the results, with an unsatisfactory explanation on	

				the theoretical and experimental/ simulation results.	
Conclusion, References and Appendix	20		15-20	Explained how the aims of the experiment have been achieved. The key features of the methods used, the most important results and the findings of the laboratory have been summarized. Complete references list to any book, articles and websites is provided with proper in-text citations in correct formatting. The appendix is provided in detail.	20
			10-15	A conclusion is drawn but is not supported by the experimental/ simulation evidence and a clear understanding of the findings. Incomplete references to the books or any other sources used in the report and the in-text citations are inappropriate or incorrect. The appendix is partially provided.	
			0-10	No sensible conclusion. The referencing is presented in the wrong format. No evidence, attachments, appendices are attached. Irrelevant referencing was used. Unclear understanding of the experiment without a summarized conclusion and the evidence of results. No appendix is provided.	
Total	100				100

Date: 7/5/2023

Examiner/ Assessor of ECE3051: Electrical Energy Systems

EXPERIMENT 1

SINGLE-PHASE AC NETWORKS

Single Element Loads

1. **Resistive Load**

ANALYSIS – Calculate the peak voltage and current from the measured rms values. Compare these values with the waveforms plotted using the CRO and hence determine the scaling factor.

Measure the time interval between zero crossings of the load voltage and the load current on the CRO and hence calculate the load phase angle. Note that 20ms = 360° on the X axis of the CRO. What is the power factor of this load? Compare the value with the reading from the V/A/W meter.

Calculate the resistance of the load-bank resistor. How does this value of resistance relate to the rating of 1500 W for the load-bank switch setting?

Analysis Answers:
(Please answer all analysis questions by including all relevant discussions, explanations, calculations, equations and figures as necessary) [6 Marks]

Calculate the peak voltage and current from the measured rms values.
from Figure 1

$I_{rms,V/A/W} = 12.17\ A$

$I_{peak,V/A/W} = I_{rms} * \sqrt{2} = 17.21A$

$V_{rms,V/A/W} = 124.4V$

$V_{peak,V/A/W} = V_{rms} * \sqrt{2} = 175.93V$

There is a difference between the calculated and the measured values. This could be due to the internal resistance of the resistor or the tolerance that exists within the resistor itself.

Compare these values with the waveforms plotted using the CRO and hence determine the scaling factor.
Channel 1

$V_{rms,CRO} = 125\ V$

$V_{peak,CRO} = V_{rms,CRO} * \sqrt{2} = 176.78\ V$

Scaling = $V_{peak,CRO} / V_{peak,V/A/W} = 1$

Channel 2

$I_{rms,CRO} = 12.9$

$I_{peak,CRO} = I_{rms,CRO} * \sqrt{2} = 18.24$

Scaling = $I_{peak,CRO} / I_{peak,V/A/W} = 1.1$

The scalings are close to 1, which is reasonable as we configured the probe and the CRO to have a scaling of one.

Measure the time interval between zero crossings of the load voltage and the load current on the CRO and hence calculate the load phase angle. Note that 20ms = 360° on the X axis of the CRO.

Time interval measured = delay of voltage - delay of current = 120us

Frequency = 50Hz

Load Phase angle, θ = f * 360 * time interval = 2.16 degree

What is the power factor of this load? Compare the value with the reading from the V/A/W meter.

Calculated power factor = cos (2.16) = 0.999

Measured power factor = 0.999

Our measured and calculated power factor are very close to each other

Calculate the resistance of the load-bank resistor. How does this value of resistance relate to the rating of 1500 W for the load-bank switch setting?

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$R_{LCR} = 10.497\ \Omega$

$Calculated\ power = V^2/R = 124.4^2 / 10.497 = 1474.27\ W$

$I_{rms,V/A/W} = 12.17\ A$

$V_{rms,V/A/W} = 124.4V$

$R_{V/A/W} = V_{rms,V/A/W}/I_{rms,\ V/A/W} = 10.22\Omega$

$Calculated\ power = V^2/R = 124.4^2 / 10.41 = 1486.59W$

$I_{rms,CRO} = 12.9\ A$

$V_{rms,\ CRO} = 125\ V$

$R_{CRO} = V_{rms,CRO}/I_{rms,\ CRO} = 9.69\ \Omega$

$Calculated\ power = V^2/R = 125^2/9.69 = 1612\ W$

All of the power obtained from the different resistance measured using LCR meters, calculations from WAV meters and CROs are close to the 1500W rating of the load bank switch. The deviations in power ratings could be attributed to the power lost across the internal resistance in the equipment.

$P = \frac{V^2}{R}$

Resistance is inversely proportional to the power rating for the load-bank switch setting.

RESULT- Show the complete workings for the calculation. Include all of the relevant calculation steps and equations. (Ensure your answer is provided with proper units) [5 Marks]

Parameter	Measured Value (Unit)	Calculated Value (Unit)	Differences
Real Power	1513 W	1500 W	13W
Reactive Power	55 VAR	0 VAR	55 VAR
Apparent Power	1514 VA	1500 VA	14 VA
V_{RMS}	124.4 V_{RMS} (V/A/W meter) 125.0 V_{RMS} (CRO)	130 V_{RMS}	5.6 V_{RMS} (V/A/W meter) 5.0 V_{RMS} (CRO)
I_{RMS}	12.17 A_{RMS} (V/A/W meter) 12.90 A_{RMS} (CRO)	11.54 A_{RMS}	0.63 A_{RMS} (V/A/W meter) 1.36 A_{RMS} (CRO)
Power Factor	0.999 (V/A/W meter) 0.999 (CRO time interval)	1	0.001 (V/A/W meter)

checked

	0.999 (CRO phase)		0.001 (CRO time interval) 0.001 (CRO phase)
Peak Voltage, V_{MAX}	175.93 V (V/A/W meter) 184.00 V (CRO)	183.847 V	7.917 V (V/A/W meter) 0.153 V (CRO)
V_{MIN}	-175.93 V (V/A/W meter) -176.00 V (CRO)	-183.847 V	7.917 V (V/A/W meter) 7.847 V (CRO)
Peak Current, I_{MAX}	17.21 A (V/A/W meter) 19.20 A (CRO)	16.32 A	0.89 A (V/A/W meter) 2.88 A (CRO)
I_{MIN}	-17.21 A (V/A/W meter) -18.02 A (CRO)	-16.32 A	0.89 A (V/A/W meter) 1.70 A (CRO)
Resistance of the load-bank resistor	10.497 Ω (LCR Meter) 10.200 Ω (V/A/W Meter) 9.690 Ω (CRO)	11.266 Ω	0.769 Ω (LCR Meter) 1.066 Ω (V/A/W Meter) 1.576 Ω (CRO)
Time interval between zero crossing	0.14 ms (V/A/W meter) 0.12 ms (CRO time interval) 0.16 ms (CRO phase)	0	0.14 ms (V/A/W meter) 0.12 ms (CRO time interval) 0.16 ms (CRO phase)
Load Phase Angle	2.56 lagging (V/A/W meter) 2.16 lagging (CRO time interval) 2.89 lagging (CRO phase)	0	2.56 lagging (V/A/W meter) 2.16 lagging (CRO time interval) 2.89 lagging (CRO phase)

Show the complete working steps to calculate all of the required parameters. [4 Marks]
Difference = |Measured - Calculated|
Real Power
Measured: 1513 W
Calculated: 1500 W (Required by labsheet)
Difference = 13 W

Reactive Power
Measured: 55 VAR
Calculated: 0 VAR

checked

As load is pure resistive, Reactive Power is 0 VAR

Difference = 55 VAR

Apparent Power
Measured: 1514 VA
Calculated: 1500 VA

$$|S_m| = \sqrt{P_m^{\ 2} + Q_m^{\ 2}}$$
$$|S_m| = \sqrt{1500^2 + 0^2}$$
$$S_m = 1500 \text{ VA}$$

Difference = 14 VA

VRMS
Measured: 124.4 V (V/A/W meter), 125 V (CRO)
Calculated: 130 V (Required by labsheet)
Difference = 5.6 V (V/A/W meter), 5.0 V(CRO)

IRMS
Measured: 12.17 A (V/A/W meter), 12.9 A(CRO)
Calculated: 11.54 A

$$Apparent\ Power/VRMS = 1500/130 = 11.54\ A$$

Difference = 0.63 A (V/A/W meter), 1.36 A (CRO)

Peak Voltage, VMAX
Measured: 175.93 V (V/A/W meter), 184 V(CRO)
For V/A/W meter

$$\text{VRMS}*\sqrt{2} = 124.4*\sqrt{2} = 175.93 \text{ V}$$

Calculated: 183.847 V

$$\text{VRMS}*\sqrt{2} = 130*\sqrt{2} = 183.847 \text{ V}$$

Difference = 7.917 V (V/A/W meter), 0.152 V (CRO)

VMIN
Measured: -175.93 V (V/A/W meter), -176 V(CRO)
Calculated: -183.847 V
Difference = 7.917 (V/A/W meter), 7.847(CRO)

Peak Current, IMAX
Measured: 17.21 A (V/A/W meter), 19.2 A(CRO)
For V/A/W meter

$$\text{IRMS}*\sqrt{2} = 12.17*\sqrt{2} = 17.21 \text{ V}$$

Calculated: 16.32A

$$\text{IRMS}*\sqrt{2} = 11.54*\sqrt{2} = 16.32\text{A}$$

Difference = 0.89 A (V/A/W meter), 2.88 A (CRO)

IMIN
Measured: -17.21 A (V/A/W meter), -18.02A(CRO)
Calculated: -16.32A
Difference = 0.89 A (V/A/W meter), 1.70 A (CRO)

checked

Resistance of the load-bank resistor
Measured: 10.497Ω (LCR Meter), 10.20 Ω(V/A/W Meter), 9.69 Ω(CRO)
For V/A/W meter

VRMS/IRMS = 124.1/12.17 = 10.20 Ω

For CRO

VRMS/IRMS =125/12.9 = 9.69 Ω

Calculated: 11.265Ω

VRMS/IRMS = 130/11.54 = 11.265 Ω

Difference: 0.768 Ω (LCR Meter), 1.065 Ω(V/A/W Meter), 1.575 Ω(CRO)

Time interval between zero crossing
Measured: 0.14ms (V/A/W meter), 120us (CRO time interval), 0.16ms(CRO phase)
Using V/A/W meter

$$load\ phase\ angle\ = 2.56$$

time interval = load phase angle/(frequency*360) = 0.14ms

Using CRO's phase

time interval = load phase angle/(frequency*360) = 0.16ms

Calculated: 0 (Theoretical due to pure resistive circuit)
Difference = 0

Load Phase Angle
Measured: 2.56 (V/A/W meter), 2.16(CRO time interval),2.89 lagging(CRO phase)
Using V/A/W meter

$$load\ phase\ angle\ = cos^{-1}(PF_{VAW})$$

$$load\ phase\ angle\ = cos^{-1}(0.999)\text{=}2.56$$

Using CRO's time interval

$$load\ phase\ angle\ = 120us * (frequency * 360) = 2.16$$

Calculated: 0

0 due to pure resistive load

Difference = 0

Power Factor
Measured: = 0.999 lagging (V/A/W meter), 0.999 (CRO time interval), 0.999 (CRO phase)
For CRO Time Interval

$$PF_{CRO\ Time\ Interval}\ = cos(2.16)\ = 0.999$$

For CRO Phase

$$PF_{CRO\ Phase}\ = cos(2.89)\ = 0.999$$

Calculated: 1

$$cos(load\ phase\ angle)\ = cos(0)\ = 1$$

Difference = 0.001

checked

Insert the snapshot (picture) of:

1. *Fluke clamp meter readings for resistive load showing active power, apparent power, reactive power, V_{RMS}, I_{RMS} and p.f.*
2. *CRO waveform of load current and load voltage with proper indication, label and scale. Note: Clearly label the voltage and current waveform.* [4 Marks]

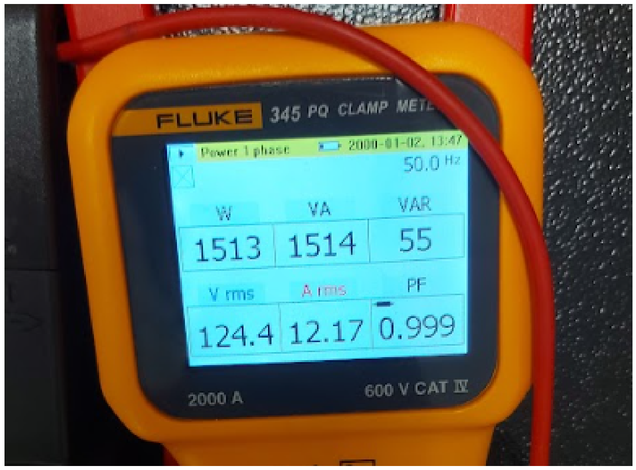
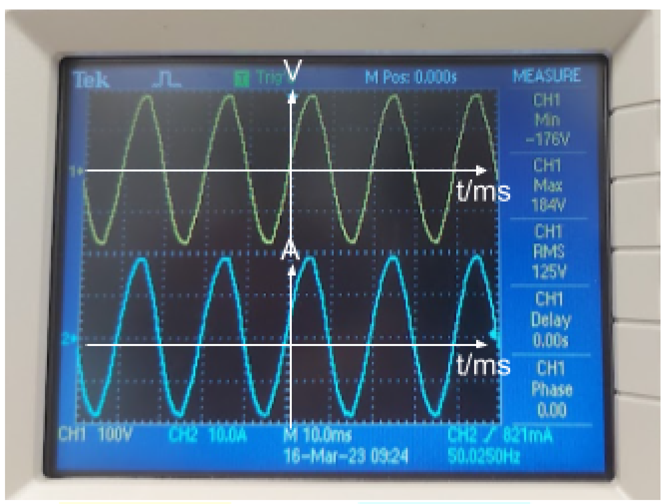


Fig. 1. V/A/W Meter Showing Power Consumed, Load Voltage and Current, and Power Factor for purely resistive load



Load Voltage	Load Current
x-scale = 1 : 10ms	x-scale = 1 : 10ms
y-scale = 1 : 100V	y-scale = 1 : 10A

Fig. 2. Voltage (Yellow) waveform along with min, max, RMS, delay, and phase measurements on the CRO for purely resistive load

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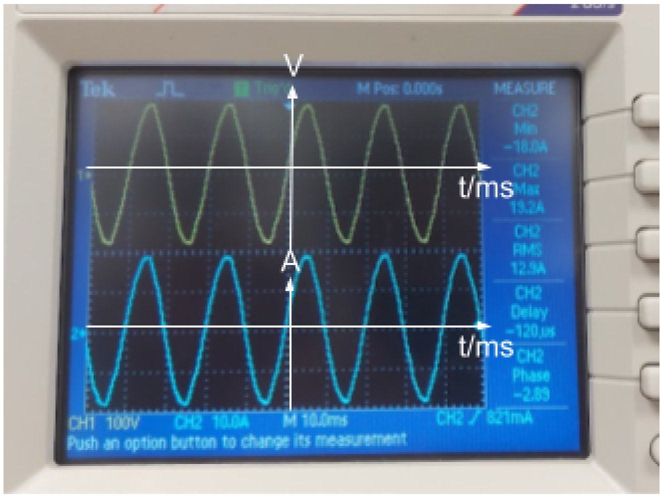

Load Voltage
x-scale = 1 : 10ms
y-scale = 1 : 100V

Load Current
x-scale = 1 : 10ms
y-scale = 1 : 10A

Fig. 3. Current (Blue) waveform along with min, max, RMS, delay, and phase measurements on the CRO for purely resistive load

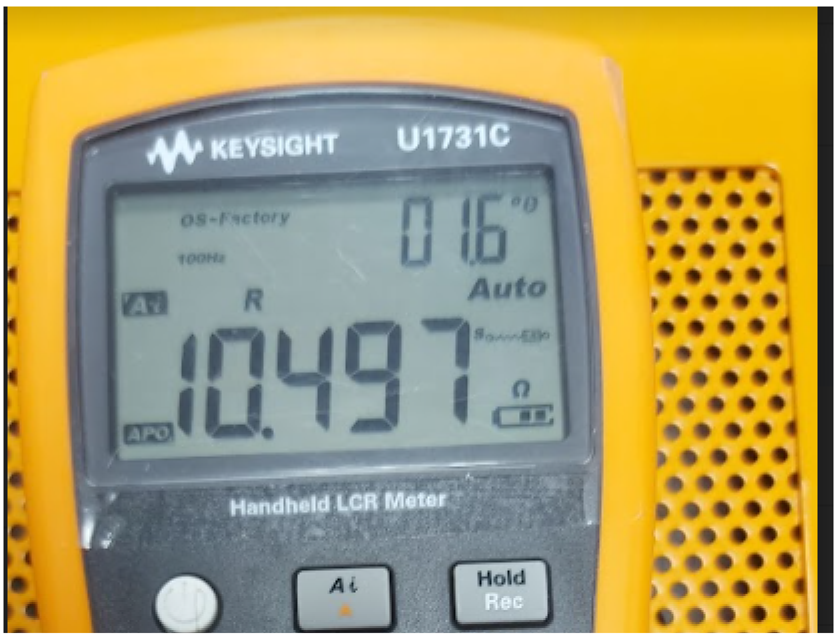

Fig. 4. LCR meter showing resistance of the load to achieve 1500W power consumption

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2. **Inductive Load**

Adjust the inductor value to a value close to 80mH by changing the switching position [**Hint:** connect two phases of the load in parallel]. Use an LCR meter for measurement.

Record the value and remove the LCR meter.

Adjust the voltage to 100 V. Measure the current, voltage and power across the

inductor. Using the CRO, plot the waveforms of load voltage and load current.

ANALYSIS – Measure the time interval between zero crossings of the load voltage and the load current on the CRO and hence calculate the load phase angle.

Is this angle exactly 90 degrees lagging? If not, why not, and what is the power factor of the inductor? Compare the value with the reading from the V/A/W meter.

Calculate the resistance and inductance value of the inductor. How does the inductance value compare with the nominal 80mH nameplate value?

Analysis Answers:
(Please answer all analysis questions by including all relevant discussions, explanations, calculations, equations and figures as necessary) [7 Marks]

Measure the time interval between zero crossings of the load voltage and the load current on the CRO and hence calculate the load phase angle.

Time interval measured = delay of voltage - delay of current = 5.56ms

Frequency = 50Hz

Load Phase angle, θ = f*360*time interval = 100.08 degree

Is this angle exactly 90 degrees lagging? If not, why not, and what is the power factor of the inductor? Compare the value with the reading from the V/A/W meter.

No, it is not exactly 90 degrees lagging, as shown by the time interval and phase measurements. This could be attributed to the presence of internal resistance that produced quite a significant active power that disrupted the 90 degree loading.

Theoretical power factor = cos (θ) = cos (90) = 0

Measured power factor (V/A/W meter) = 0.108

Measured power factor (CRO Phase) = cos(100.08) = 0.18

Measured power factor (CRO Time Interval) = cos(99.89) = 0.16

Calculate the resistance and inductance value of the inductor. How does the inductance value compare with the nominal 80mH nameplate value?

We can calculate the resistance from the Real Power and Irms over the load, and the inductance from

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the Reactive Power and Irms. We assume the load only have resistance and inductance, with no capacitance $P = I^2R$ $67 = (5.75^2)R$ $R = 2.03\Omega$ $Q = I^2X_m$ $572 = (5.75^2)X_l$ $X_m = 17.3j\,\Omega$ Using Xm, we can further calculate the inductance by disregarding capacitance $X_l = \omega L$ $17.3 = 2\pi \times 50 * L$ $L = 55.07mH$ The inductance value deviates from the 80mH by 31%, which could be caused by stray capacitance in the inductor load that reduced the total reactance of the load.

RESULT- Show the complete workings for the calculation. Include all the relevant calculation steps and equations. (Ensure your answer is provided with proper units) [5 Marks]

Parameter	Measured Value (Unit)	Calculated Value (Unit)	Differences
Real Power	67 W	0 W	67 W
Reactive Power	576 VAR	397.84 VAR	178.16 VAR
Apparent Power	572 VA	397.84 VA	174.16 VA
V_{RMS}	100.3 V_{RMS} (V/A/W meter) 101.0 V_{RMS} (CRO)	100 V_{RMS}	0.3 V_{RMS} (V/A/W meter) 1.0 V_{RMS} (CRO)
I_{RMS}	5.75 A_{RMS} (V/A/W meter) 6.12 A_{RMS} (CRO)	3.98 A_{RMS}	1.77 A_{RMS} (V/A/W meter) 2.14 A_{RMS} (CRO)
Power Factor	0.116 (V/A/W meter) 0.18 (CRO time interval) 0.18 (CRO phase)	0	0.116 (V/A/W meter) 0.18 (CRO time interval)

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			0.18 (CRO phase)
Peak Voltage, V_{MAX}	141.84 V (V/A/W meter) 148 V(CRO)	141.42V	0.42 V_{MAX} (V/A/W meter) 6.58 V_{MAX} (CRO)
V_{MIN}	-141.84 V (V/A/W meter) -144 V(CRO)	-141.42V	0.42 V_{MIN} (V/A/W meter) 2.58 V_{MIN} (CRO)
Peak Current, I_{MAX}	8.13 A (V/A/W meter) 9.6 A(CRO)	5.614A	2.516 A (V/A/W meter) 3.986 A (CRO)
I_{MIN}	-8.13 A (V/A/W meter) -8.8 A (CRO)	-5.614A	2.516 A (V/A/W meter) 3.186 A (CRO)
Inductance from LCR meter	78.01mH (LCR Meter) 55. 06mH (V/A/W Meter)	80mH	1.99 mH (LCR Meter) 24.94 mH (V/A/W Meter)
Time interval between zero crossing	4.63ms (V/A/W meter) 5.56ms (CRO time interval) 5.55ms (CRO phase)	5 ms	0.37 ms 0.56 ms 0.55 ms
Load Phase Angle	83.34 lagging (V/A/W meter) 100.08 lagging (CRO time interval) 99.89 lagging (CRO phase)	90° lagging	6.66° 10.08 ° 9.89 °

Show the complete working steps to calculate all of the required parameters. [4 Marks]

Difference = |Measured - Calculated|
Real Power
Measured: 67 W
Calculated: 0 W (Assumed Pure Inductive)
Difference = 67 W

checked

Reactive Power
Measured: 572 VAR
Calculated: $397.84\,VAR$

$$V = 100V$$
$$L = 80mH$$
(Assume Pure Inductor)
$$Z = 2 * \pi i * f * L = 2 * \pi * 50 * 80mH = 25.13j$$
$$I = V/Z_m = 100/25.13 = 3.98A$$
$$Q_m = I^2 Z_m = 3.98^2 * 25.13 = 397.84\,VAR$$

Difference = VAR

Apparent Power
Measured: 576 VA
Calculated: 397.84VA

$$|S_m| = \sqrt{P_m^{\ 2} + Q_m^{\ 2}}$$
$$S_m = \sqrt{0^2 + 397.84^2}$$
$$S_m = 397.84\,VA$$

Difference = 178.16 VA

VRMS
Measured: 100.3 V (V/A/W meter), 101 V (CRO)
Calculated: 100 V (Required by labsheet)
Difference = 0.3 V (V/A/W meter), 1.0 V (CRO)

IRMS
Measured: 5.75 A (V/A/W meter), 6.12 A (CRO)
Calculated: 3.98 A

Apparent Power/VRMS = 397.93/100 = 3.98 A

Difference = 1.77 A (V/A/W meter), 2.14 A (CRO)

Peak Voltage, VMAX
Measured: 141.84 V (V/A/W meter), 148 V (CRO)
For V/A/W meter

VRMS*$\sqrt{2}$ = 100.3*$\sqrt{2}$= 141.84 V

Calculated: 141.42 V

VRMS*$\sqrt{2}$ = 100*$\sqrt{2}$= 141.42 V

Difference = 0.42 V(V/A/W meter), 6.58 V (CRO)

VMIN
Measured: -141.84 V (V/A/W meter), -144 V (CRO)
Calculated: -141.42 V
Difference = 0.42 V (V/A/W meter), 2.58 V (CRO)

checked

Peak Current, IMAX
Measured: 8.13 A (V/A/W meter), 9.6 A(CRO)

$$IRMS*\sqrt{2} = 5.75*\sqrt{2}= 8.13 \text{ A}$$

Calculated: 5.61 A

$$IRMS*\sqrt{2} = 3.97*\sqrt{2}= 5.61\text{A}$$

Difference = 2.52 A (V/A/W meter), 3.99 A (CRO)

IMIN
Measured: -8.13 A (V/A/W meter), -8.8 A(CRO)
Calculated: -5.61A
Difference = 2.52 A (V/A/W meter), 3.19 A(CRO)

Inductance from LCR meter

Measured: 79.93mH (LCR Meter)

Calculated: 80mH (as required by labsheet)

Difference = 0.07 mH

Time interval between zero crossing
Measured: 4.63ms (V/A/W meter), 5.56ms (CRO time interval), 5.55ms (CRO phase)
Using V/A/W meter

$$load\ phase\ angle\ = 83.34$$

time interval = load phase angle/(frequency*360) = 4.63ms

Using CRO's phase

time interval = load phase angle/(frequency*360) = 5.55ms

Calculated: 5ms (Theoretical)

pure inductive circuit will have a 90 degree load phase angle

frequency = 50Hz

frequency*360*time interval = load phase angle

time interval = 90/(360*50)=5ms

Difference = 0

Load Phase Angle
Measured: 83.34 (V/A/W meter), 100.08(CRO time interval), 99.89(CRO phase)
Using V/A/W meter

$$load\ phase\ angle\ = cos^{-1}(PF_{VAW})$$

$$load\ phase\ angle\ = cos^{-1}(0.108) = 83.34$$

Using CRO's time interval

$$load\ phase\ angle\ = time\ interval * (frequency * 360)$$

Calculated: 90 lagging

90 lagging due to purely inductive load

checked

Difference = 0

Power Factor
Measured: = 0.116 lagging (V/A/W meter), 0.18 lagging(CRO time interval), 0.17 lagging(CRO phase)
For CRO Time Interval

$$PF_{CRO\ Time\ Interval} = cos(load\ phase\ angle) = 0.18$$

For CRO Phase

$$PF_{CRO\ Phase} = cos(load\ phase\ angle) = 0.17$$

Calculated: cos(load phase angle measured) = cos(90) = 0
0 lagging due to purely inductive load

Difference = 0.116 lagging (V/A/W meter), 0.18 lagging(CRO time interval), 0.17 lagging(CRO phase)

Insert the snapshot (picture) of:

3. *Fluke clamp meter readings for resistive load showing active power, apparent power, reactive power, V_{RMS}, I_{RMS} and p.f.*
4. *CRO waveform of load current and load voltage with proper indication, label and scale. Note: Clearly label the voltage and current waveform.* [4 Marks]

Picture of V/A/W Meter

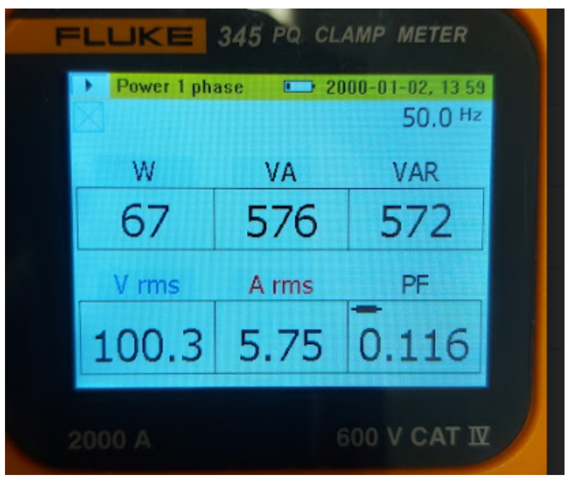

Fig. 5. V/A/W Meter Showing Power Consumed, Load Voltage and Current, and Power Factor for purely inductive load

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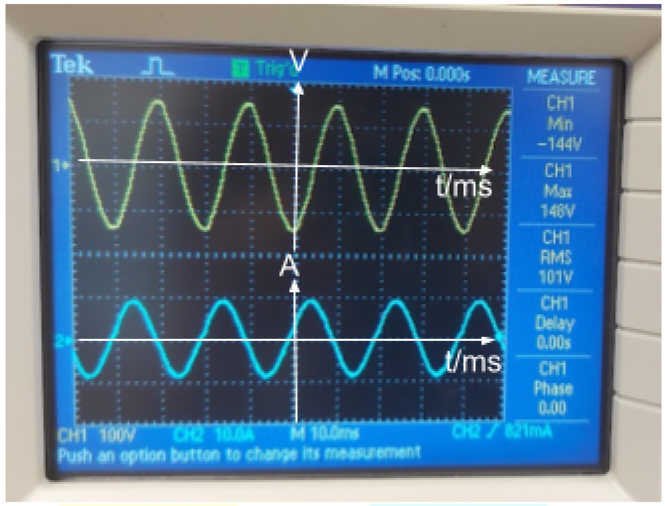
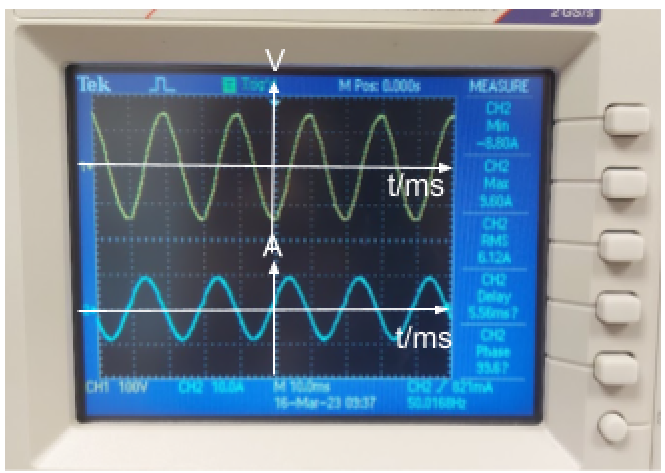


Load Voltage
x-scale = 1 : 10ms
y-scale = 1 : 100V

Load Current
x-scale = 1 : 10ms
y-scale = 1 : 10A

Fig. 6. Voltage (Yellow) waveform along with min, max, RMS, delay, and phase measurements on the CRO for purely inductive load



Load Voltage
x-scale = 1 : 10ms
y-scale = 1 : 100V

Load Current
x-scale = 1 : 10ms
y-scale = 1 : 10A

Fig. 7. Current (Blue) waveform along with min, max, RMS, delay, and phase measurements on the CRO for purely inductive load

Note:
For an inductive load the current graph should be lagging the voltage graph by 5ms. Due to the reversed polarities at the terminals during measurement, the measured graphs in figure (7) & (8) shows current leading voltage which is erroneous.

checked

Picture of LCR Meter

Fig. 8. LCR meter showing inductor bank's inductor value

3. **Capacitive Load**

Switch the capacitive load on (by taking the first switch to position '1') and adjust the capacitor value to a value close to 40 µF by changing the second switch [**Hint:** connect two phases of the load in parallel]. Use an LCR meter for measurement. Record the value and remove the LCR meter.

Adjust the voltage to 130 V. Measure the current, voltage and power across the

capacitor. Using the CRO, plot the waveforms of load voltage and load current.

ANALYSIS – Measure the time interval between zero crossings of the load voltage and the load current on the CRO and hence calculate the load phase angle.

Is this angle exactly 90 degrees leading? If not, why not? What is the power factor of the capacitor? Compare the value with the reading from the V/A/W meter.

Calculate the capacitance value of the capacitor. How does this value compare with the nominal 40 µF nameplate value?

Comment on the shape of the capacitor current – is it sinusoidal? If no, try and determine the dominant harmonic frequencies present from the ripple. Why is this effect more noticeable for capacitor load, compared to the resistive and inductive load?

WARNING: Discharge the capacitor bank (bring the first switch back to position '0').

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Measure the time interval between zero crossings of the load voltage and the load current on the CRO and hence calculate the load phase angle.

Time interval measured = delay of voltage - delay of current = 4.84ms

Frequency = 50Hz

Load Phase angle, θ = f*360*time interval = 87.12

Is this angle exactly 90 degrees leading? If not, why not? What is the power factor of the capacitor? Compare the value with the reading from the V/A/W meter.
No, it is not exactly 90 degrees leading, but it is approximately close, as shown by the time interval and phase measurements. It could be due to the internal resistance that produces active power that disrupted the 90 degree loading of the phasor.

Theoretical power factor = cos (θ) = cos (90) = 0

Measured power factor (V/A/W meter) = 0.027

Measured power factor (CRO Phase) = 0.05

Measured power factor (CRO Time Interval) = 0.05

The pf values obtained from the VAW and CRO readings are approximately close

Calculate the capacitance value of the capacitor. How does this value compare with the nominal 40 µF nameplate value?

We can calculate the resistance from the Real Power and Irms over the load, and the capacitance from the Reactive Power and Irms. We assume the load only have resistance and inductance, with no capacitance

$P = I^2R$

$6 = (1.68^2)R$

$R = 2.12\,\Omega$

$Q = I^2X_m$

$219 = (1.68^2)X_l$

$X_m = 77.59\,\Omega$

Using Xm, we can further calculate the inductance by disregarding capacitance

$X_l = 1/(wC)$

$77.59 = 1/(2\pi * 50 * C)$

$C = 41\,uF$

checked

The inductance value deviates from the uF by 2.56%, which could be caused by stray inductance in the inductor load that increases the total reactance of the load.

Comment on the shape of the capacitor current – is it sinusoidal? If no, try and determine the dominant harmonic frequencies present from the ripple. Why is this effect more noticeable for capacitor load, compared to the resistive and inductive load?
The shape of the capacitor current is sinusoidal with ripples in the waveform. We determine the dominant frequency to 50Hz which is the frequency of the source voltage. The frequency in the ripples could be caused by a high frequency noise.

This effect is not noticeable in the resistive load current as the impedance of the resistive load remains the same regardless of frequency of the source.

The effect is not noticeable in inductive load current as impedance of inductors increases as frequencies increases, thus high frequency noise in the source is attenuated by the impedance

The effect is most noticeable in capacitive loads due to its impedance being inversely proportional to the source frequency. The high frequency noise has lesser impedance, and thus is able to draw high frequency current from the source, thus creating the high frequency ripples in the waveform.

RESULT- Show the complete workings for the calculation. Include all the relevant calculation steps and equations. (Ensure your answer is provided with proper units) [5 Marks] **(Note: the power was taken in reverse by accident)**

Parameter	Measured Value (Unit)	Calculated Value (Unit)	Differences
Real Power	6W	0W	6W
Reactive Power	219 VAR	212. 38VAR	6.62VAR
Apparent Power	220 VA	212. 38 VA	7.62VA
V_{RMS}	130.8 V (V/A/W meter) 131 V (CRO)	130 V	0.8V_{RMS} (V/A/W meter) 1.0V_{RMS} (CRO)
I_{RMS}	1.68 A (V/A/W meter) 1.86 A (CRO)	1. 63A	0.05A (V/A/W meter) 0.23A (CRO)
Power Factor	0.027 (V/A/W meter) (CRO time interval) 0.05 (CRO phase)	0	0.027 (V/A/W meter) (CRO time interval) 0.05 (CRO phase)

checked

Peak Voltage, V_{MAX}	184.98 V (V/A/W meter) 192 V(CRO)	183.85V	1.13 V (V/A/W meter) 8.15 V(CRO)
V_{MIN}	-184.98 V (V/A/W meter) -185 V(CRO)	-183.85V	1.13 V (V/A/W meter) 1.15 V(CRO)
Peak Current, I_{MAX}	2.38 A (V/A/W meter) 3.6 A (CRO)	2.305A	0.075 A (V/A/W meter) 1.295 A(CRO)
I_{MIN}	-2.38 A (V/A/W meter) -2.64 A(CRO)	-2.305A	0.075 A (V/A/W meter) 0.335 A (CRO)
Capacitance from LCR meter	40.81 uF (LCR Meter) 41 uF (V/A/W Meter)	40uF	0.81 mH (LCR Meter) 1.00 mH (V/A/W Meter)
Time interval between zero crossing	4.91 ms (V/A/W meter) 4.84 ms (CRO time interval) 4.83 ms (CRO phase)	5 ms	0.09 ms (V/A/W meter) 0.16 ms (CRO time interval) 0.17 ms (CRO phase)
Load Phase Angle	88.45 leading(V/A/W meter) 87.12 leading (CRO time interval) 86.9 leading (CRO phase)	90° leading	1.55 leading(V/A/W meter) 2.88 leading (CRO time interval) 3.10 leading (CRO phase)

Show the complete working steps to calculate all of the required parameters. [4 Marks]
Difference = |Measured - Calculated|
Real Power
Measured: 6 W
Calculated: 0 W (Assumed Pure Inductive)
Difference = 6 W

Reactive Power

Measured: 219 VAR
Calculated: 212.38 VAR

$$V = 100V$$
$$L = 40uF$$
(Assume Pure Capacitor)
$$Z = 1/(2 * \pi i * f * L) = 1/(2 * \pi * 50 * 80mH) = 79.58j\,\Omega$$
$$I = V/Z_m = 130/79.58 = 1.63A$$
$$Q_m = I^2 Z_m = 1.63^2 * 79.58 = 212.38\,VAR$$

Difference = 6.62 VAR

Apparent Power
Measured: 220 VA
Calculated: 212.38VA

$$|S_m| = \sqrt{P_m^{\ 2} + Q_m^{\ 2}}$$
$$S_m = \sqrt{0^2 + 212.38^2}$$
$$S_m = 212.38\,VA$$

Difference = 7.62 VA

VRMS
Measured: 130.8 V (V/A/W meter), 131 V(CRO)
Calculated: 130 V (Required by labsheet)
Difference = 0.8 V (V/A/W meter), 1.0 V (CRO)

IRMS
Measured: 1.68 A (V/A/W meter), 1.86 A(CRO)
Calculated: 1.63 A

Apparent Power/VRMS = 212.38/130 = 1.63 A

Difference = 0.05 A (V/A/W meter), 0.23 A (CRO)

Peak Voltage, VMAX
Measured: 184.98 V (V/A/W meter), 192 V(CRO)
For V/A/W meter

VRMS*$\sqrt{2}$ = 130.8*$\sqrt{2}$= 184.98 V

Calculated: 183.85 V

VRMS*$\sqrt{2}$ = 130*$\sqrt{2}$= 183.85 V

Difference = 1.13 V (V/A/W meter), 8.15 V (CRO)

VMIN
Measured: -184.98V (V/A/W meter), -185 V(CRO)
Calculated: -183.85 V
Difference = 1.13 V (V/A/W meter), 1.15 V (CRO)

Peak Current, IMAX

checked

Measured: 2.38 A (V/A/W meter), 3.6 A(CRO)

$$IRMS*\sqrt{2} = 1.68*\sqrt{2} = 2.38A$$

Calculated: 2.305A

$$IRMS*\sqrt{2} = 1.63*\sqrt{2} = 2.305A$$

Difference = 0.075 A (V/A/W meter), 1.295 A (CRO)

IMIN
Measured: -2.38 A (V/A/W meter), -2.64 A (CRO)
Calculated: -2.305 A
Difference = 0.075 A (V/A/W meter), 0.335 A (CRO)

Capacitance from LCR Meter

Measured: 40.81uF (LCR Meter)

Calculated: 40uF (as required by labsheet)

Difference = 0.81uF

Time interval between zero crossing
Measured: 4.91ms (V/A/W meter), 4.84ms (CRO time interval),4.83ms (CRO phase)
Using V/A/W meter

time interval = load phase angle/(frequency*360) = 88.45/(50*360) = 4.91ms'

Using CRO's phase

time interval = load phase angle/(frequency*360) =86.9/(50*360) = 4.83ms

Calculated: 5ms (Theoretical)

pure capacitive circuit will have a 90 degree load phase angle

frequency = 50Hz

frequency*360*time interval = load phase angle

time interval = 90/(360*50)=5ms

Difference = 0.17ms

Load Phase Angle
Measured: 88.45 (V/A/W meter),87.12 (CRO time interval),86.9 (CRO phase)
Using V/A/W meter

$$load\ phase\ angle\ = cos^{-1}(0.027) = 88.45$$

Using CRO's time interval

$$load\ phase\ angle\ = time\ interval\ *\ (frequency\ *\ 360)\ =\ 4.84m\ *\ 50\ *\ 360\ =\ 87.12$$

Calculated: 90 Leading

90 leading due to purely capacitive load

Difference = 1.55 (V/A/W meter), 2.88 (CRO time interval), 3.10 (CRO phase)

checked

Power Factor

Measured: = 0.027 leading(V/A/W meter), 0.05(CRO time interval),0.05 (CRO phase)

For CRO Time Interval

$$PF_{CRO\ Time\ Interval} = cos(87.12) = 0.05$$

For CRO Phase

$$PF_{CRO\ Phase} = cos(86.9) = 0.05$$

Calculated: cos(load phase angle measured) = cos(90) = 0

0 leading due to purely capacitive load

Difference: 0.027 leading(V/A/W meter), 0.05(CRO time interval),0.05 (CRO phase)

Insert the snapshot (picture) of:

5. *Fluke clamp meter readings for resistive load showing active power, apparent power, reactive power, V_{RMS}, I_{RMS} and p.f.*
6. *CRO waveform of load current and load voltage with proper indication, label and scale. Note: Clearly label the voltage and current waveform.* [4 Marks]

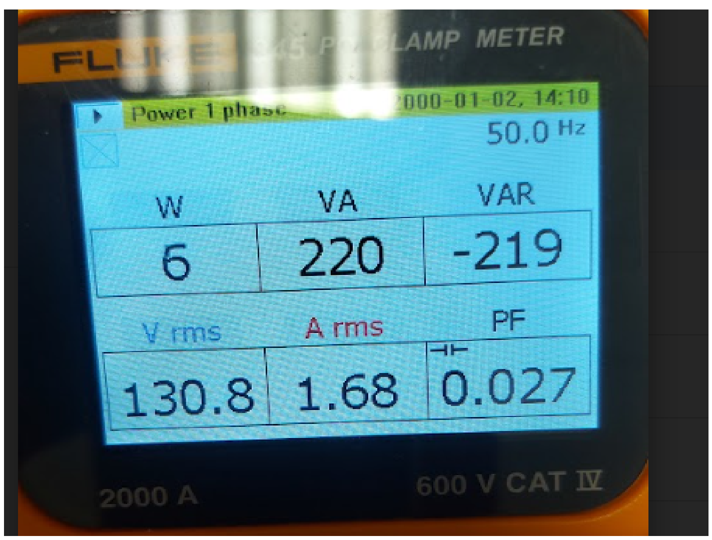

Fig. 9. V/A/W Meter Showing Power Consumed, Load Voltage and Current, and Power Factor for purely capacitive load

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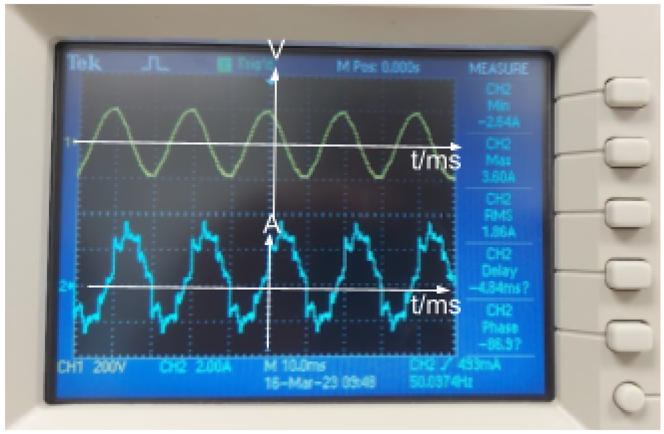
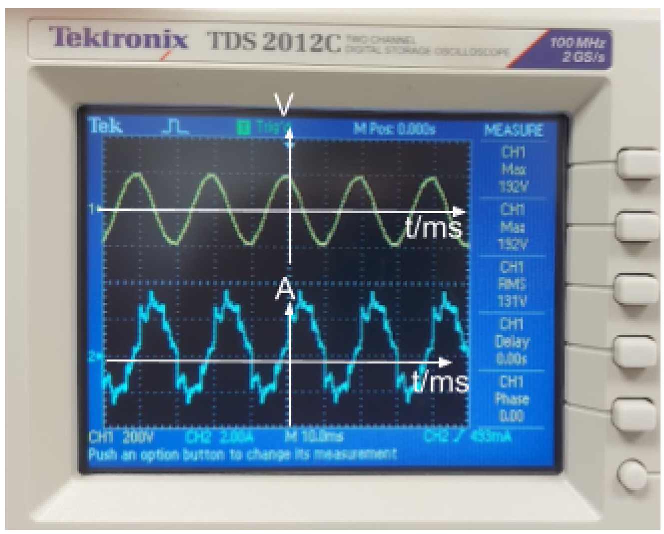


Load Voltage
x-scale = 1 : 10ms
y-scale = 1 : 200V

Load Current
x-scale = 1 : 10ms
y-scale = 1 : 2A

Fig. 10. Voltage (Yellow) waveform along with min, max, RMS, delay, and phase measurements on the CRO for purely capacitive load



Load Voltage
x-scale = 1 : 10ms
y-scale = 1 : 200V

Load Current
x-scale = 1 : 10ms
y-scale = 1 : 2A

Fig. 11. Current (Blue) waveform along with min, max, RMS, delay, and phase measurements on the CRO for purely capacitive load

Note:
For a capacitive load the current graph should be leading the voltage graph by 5ms. Due to the reversed polarities at the terminals during measurement, the measured graphs in figure (10) & (11) shows current lagging voltage which is erroneous.

checked

Fig. 12. LCR meter showing the capacitor bank's value

Discussion

1. What are the differences in terms of power components for resistive, capacitive and inductive elements in an AC circuit? What is the definition of power factor and apparent power? How can the power factor be expressed in terms of circuit impedance and circuit power? [10 Marks]

What are the differences in terms of power components for resistive, capacitive and inductive elements in an AC circuit?

The power components for resistive elements is known as active power, measured in Watts, or also known as true power. This is the power that is used to do useful work in a system and powers the system. Resistive components, such as resistors, consume power in proportion to the square of current flowing through, and dissipates in the form of heat energy

The power components for capacitive and inductive elements are known as reactive power, measured in VAR. Reactive power is needed to generate a magnetic field and flux in its applications. For capacitive loads, the phase of the current will lead behind the voltage phase, while in inductive load, the phase of the current will lag behind the voltage phase.

Capacitive components store energy in the electric field, whereas inductive components store energy in the magnetic field, they do not consume real power, but affect the power consumed by other components.

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What is the definition of power factor and apparent power?
Power factor refers to the ratio of real power to the apparent power in an AC circuit. Apparent power is the magnitude of the vectorial sum of the real and reactive power

How can the power factor be expressed in terms of circuit impedance and circuit power?
pf = cos(arctan(X/R)) or pf = R/Z

pf = P/|S|

where X is the reactance of the system, R is the resistance of the system, P is the real power of the system, and S is the complex power of the system.

Power factor can also be calculated by the angle between real power (P) and complex power (S), which is the cosine of the angle of the circuit impedance

2. What are the difficulties encountered during the experiment? Justify the differences between the measured values and calculated values if there are any discrepancies? In your opinion, which of the obtained values (measured values or calculated values) are more accurate? In real-world practice, suggest at least five steps which can be taken to prevent any measurement error(s)? [10 Marks]

The difficulties of this experiment is the inexperience of handling the equipment. As this is the first time we ever encountered high voltage-high current equipment, we had a hard time trying to work around it and familiarizing ourselves with the procedures to use it. While the lab supervisor did demonstrate the necessary steps in the experiment, he needs to understand that students need practice and time to get used to the equipment, and not just questioning whether the student was paying attention or not when students are seeking assistance.

There were discrepancies in the values measured and calculated, which can be attributed to the non-ideality of the lab equipment such as internal resistance, stray inductance and stray capacitance in different equipment. Calibration errors and loose connections in the setup could also lead to the discrepancy in values.

In my opinion, the measured values should be more accurate as it reflects real life non-idealities of the equipment.. The calculated values only present a guideline to how far the values can deviate when measured. However, this only holds true provided all preventive measures have been taken care of, which would be explained below.

In real world practice, to prevent any measurement errors, the following steps can be taken
- *Calibrate any measuring equipment to prevent errors like zero offset errors*
- *Check the initial setup of all equipment (CRO probes and scaling, tight connections etc.) to make sure that the there is no mistakes in the setup that could lead to wrong measurements*
- *Always perform safety measures taught in the lab, like turning on the power supply only when resistance is maximum to limit current flow, turning off the power supply when not in use, turning off measuring equipment when not in use. All of these measures serve to lengthen the shelf life of the equipment and allow it to be accurate when measuring.*

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- *The experiment has to be conducted in a controlled environment that is free from environment variables like temperature.*
- *Multiple measurements can be taken and averaged out to reduce the possibility of measurement error.*

Conclusion and Findings [14 Marks]

This experiment introduced us to single phase AC networks and demonstrated the relationship between voltage and current with different types of load - resistive, inductive, and capacitive.

The experimental results prove the following statements:

When the load is purely resistive, both the voltage and current are in phase [1], [2]. A purely resistive load consumes only real power, which means that the reactive power in the system is zero, and that the total apparent power is equal to the real power. Since the power factor is the cosine of the phase difference between the voltage and current [1], [5], or the ratio between real power and apparent power [1], [5], the system must have a power factor of one. However, in a real environment, where there are parasitic inductance and capacitance within the components of the system, the power factor can never be one, but close to it.

When the load is purely inductive, the current ***lags*** *the voltage with a phase difference of 90 degrees [1], [2]. A purely inductive system consumes only reactive power and therefore, the real power consumed must be zero, and that the total apparent power equals the reactive power. Using the definition of power factor defined in the paragraph above, the power factor of a purely inductive circuit must be zero. In a real environment where nothing is ideal, there is bound to be internal resistance in the components of the system, which only allows the power factor to be close to zero but never exactly zero.*

When the load is purely capacitive, the current ***leads*** *the voltage with a phase difference of 90 degrees [1], [2]. Similar to purely inductive loads, the apparent power of the system is fully converted into reactive power. This means that the power factor of a purely capacitive circuit is also zero. However, the presence of internal resistances within components like wires, power supplies, etc., are bound to consume some real power, causing the power factor to be close to zero but never exactly zero.*

By investigating these three basic types of load, we can conclude that more complicated loads are just a combination of R, L, and C components [3]. Simply put, all types of load can be represented by having a certain weightage of resistive, inductive, and capacitive components. The power factor of the load will then be determined by how much real and reactive power the load consumes, and the dominant type of load will dictate whether the power factor is close to unity, leading, or lagging [4].

In summary, we have learnt the distinctions and characteristics of resistive, capacitive, and inductive loads. We have observed how similar the theoretical values align with the experimental values obtained. Although they are not completely identical, we can say with confidence that these deviations are expected due to non-controllable factors such as internal resistances and parasitic inductance or capacitance [6].

checked

References (Minimum 3 References) [6 Marks]

[1] C. R. Sarimuthu, "Power Systems Analysis- AC Systems", ECE3051 - Electrical Energy Systems, Department of Electrical and Computer Systems Engineering, Monash University Malaysia, 2020

[2] A. Javeri, "Top 3 Types of Electrical Load - Resistive, Inductive & Capacitive", 2022, https://www.ny-engineers.com/blog/top-3-types-of-electrical-load-resistive-inductive-capacitive (Accessed on 16 March 2023).

[3] K. Beck, "Types of Electrical Loads", 2018, https://sciencing.com/types-electrical-loads-8367034.html (Accessed on 16 March 2023).

[4] Fluke, "What is Power Factor and Why Is It Important?", https://www.fluke.com/en-my/learn/blog/power-quality/power-factor-formula#:~:text=It%20is%20found%20by%20multiplying,than%20a%2075%25%20power%20factor. (Accessed on 16 March 2023).

[5] All About Circuits, "Calculating Power Factor", https://www.allaboutcircuits.com/textbook/alternating-current/chpt-11/calculating-power-factor/ (Accessed on 16 March 2023).

[6] Electrical Engineering Info, "Different Types of Errors in Electrical Measuring Instruments", 2016, https://www.electricalengineeringinfo.com/2016/11/what-different-types-of-errors-in-electrical-measuring-instruments-gross-systematic-random.html (Accessed on 16 March 2023).

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MONASH University MALAYSIA

SCHOOL OF ENGINEERING

ELECTRICAL AND COMPUTER SYSTEMS ENGINEERING

LABORATORY REPORT MARKING RUBRIC

ECE3051: ELECTRICAL ENERGY SYSTEMS

Experiment Number: 2

Title of Lab Sheet: Single Phase Diode Rectifiers

Group Number: 8

No.	Student ID	Name of Group Members	Total Marks
1	30720230	Loh Jia Quan	99.5/100
2	31106889	Agill Kumar Saravanan	99.5/100
3	30719305	Huan Meng Hui	99.5/100
4	32194471	Tan Jin Chun	99.5/100
5	32259417	Chong Yen juin	99.5/100

MARKS BREAKDOWN

Section	Total Score	Actual Marks	Scoring Band	Criteria	Comment
Results	40		30-40	Clear and completely labelled figures of the experiment/simulation results with justifications and tables. A detailed caption is provided for each figure with an in-text figure reference. The x-axis and y-axis are labelled with the unit in the bracket. The legend is provided whenever it is deemed to be required. If there is more than one line, the lines should be clearly distinguishable with the visible difference such as dotted line, dashed line and solid line, even in black and white.	39.5
			20-30	Some of the figures of the experiment/simulation setup are not clear, do not have any labelling/ caption/ in-text caption reference/ distinguishable multiple lines and are blurry. The table and justification have mistakes or errors.	
			0-20	Insufficient amounts of figures and labelling of the experiment/simulation layout setup, which is not correct and/or unclear. The table is not filled.	
Discussion	40		30-40	Complete data collection and presentation using tables/figures/ graphs with appropriate labels. Discussion of the results with prudent judgment. Have a comparison of the measured results with theoretical values and in-text citations from the peer-reviewed references. The comprehensive comparison, evaluation and justification of the results are given with clear explanation to demonstrate the understanding of the laboratory.	40
			20-30	The discussion shows little understanding of what the experiment/simulation is all about. Brief comparison, evaluation and justification of the results, with unclear/ incorrect explanation on the theoretical and experimental/ simulation results.	
			0-20	Only restatement of the results without commenting on the expected key points. Incorrect judgment/ arguments were used. No comparison, evaluation and justification of the results, with an unsatisfactory explanation on the theoretical and experimental/ simulation results.	
Conclusion, References and Appendix	20		15-20	Explained how the aims of the experiment have been achieved. The key features of the methods used, the most important results and the findings of the laboratory have been summarized. Complete references list to any book, articles and websites is provided with proper in-text citations in correct formatting. The appendix is provided in detail.	$\boxed{20}$

			10-15	A conclusion is drawn but is not supported by the experimental/ simulation evidence and a clear understanding of the findings. Incomplete references to the books or any other sources used in the report and the in-text citations are inappropriate or incorrect. The appendix is partially provided.	
			0-10	No sensible conclusion. The referencing is presented in the wrong format. No evidence, attachments, appendices are attached. Irrelevant referencing was used. Unclear understanding of the experiment without a summarized conclusion and the evidence of results. No appendix is provided.	
Total	100				99.5

Examiner/ Assessor of ECE3051: Electrical Energy Systems

Date: 15/4/2023

EXPERIMENT 2

SINGLE PHASE DIODE RECTIFIERS

Full Wave Diode Circuits

1. Resistive Load: 18.8 Ω

Experimental setup [2.5 Marks]

(Draw the circuit diagram. State the required measured values and waveforms.)

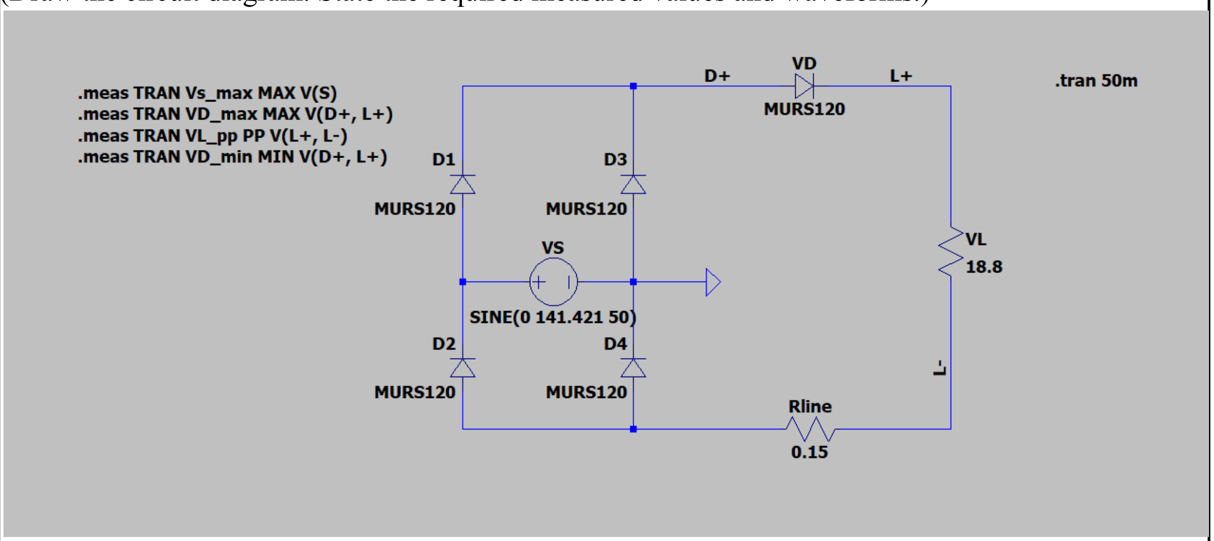

Fig.1 LTSpice Schematic of Resistive Load

The required measured values are

1. The peak value of V_S, the source voltage
2. The average value (mean) of V_L, the load resistor voltage
3. The voltage across the rectifying diode, V_D

```
SPICE Error Log: C:\Users\Chong Yen Juin\Desktop\Monash\ECE3051\Lab_2\Resistive_Load.log
Circuit: * C:\Users\Chong Yen Juin\Desktop\Monash\ECE3051\Lab_2\Resistive_Load.asc

.OP point found by inspection.

vs_max: MAX(v(s))=141.348 FROM 0 TO 0.05
vd_max: MAX(v(d+, l+))=1.02501 FROM 0 TO 0.05
vl_pp: PP(v(l+, l-))=137.171 FROM 0 TO 0.05
vd_min: MIN(v(d+, l+))=-8.61976e-06 FROM 0 TO 0.05


Date: Tue Mar 28 23:22:55 2023
Total elapsed time: 0.096 seconds.

tnom = 27
temp = 27
method = modified trap
totiter = 2711
traniter = 2711
tranpoints = 1245
accept = 1182
rejected = 63
matrix size = 11
fillins = 0
solver = Normal
Avg thread counts: 1.2/1.5/1.5/1.2
Matrix Compiler1: 504 bytes object code size  0.3/0.3/[0.2]
Matrix Compiler2: 787 bytes object code size  0.2/0.4/[0.1]
```

Fig.2 LTSpice Simulation Result of Resistive Load

checked

Calculation to get mean load voltage

?

$V_{L\ (peak\text{-}to\text{-}peak)}$ =137.171 V□ $V_{L,mean} = \frac{2*137.171}{\pi} = 87.326V$ minus 0.5 mark

Required waveforms:
Waveform 1: V_s, V_L and V_D

Actual Measurements

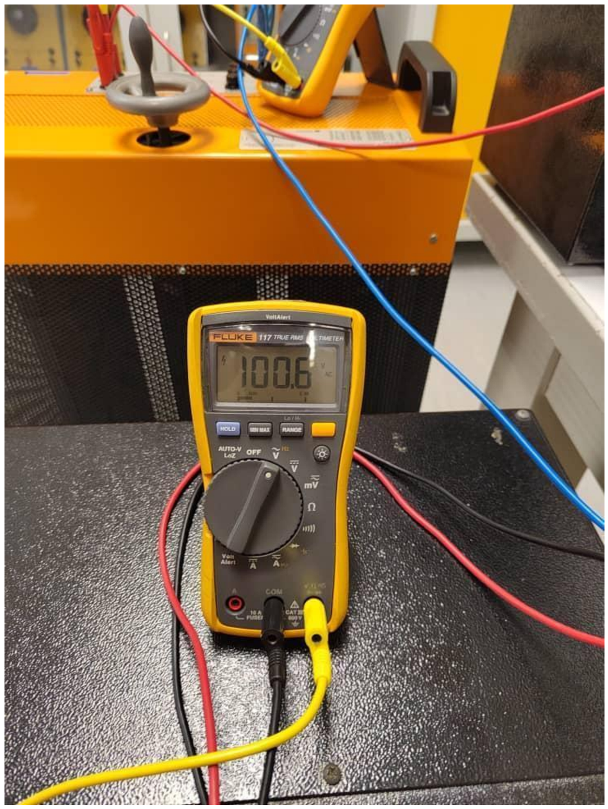

Fig 3. RMS value of source voltage, V_S measured by multimeter.

$$V_{s_{peak}} = 100\,V \;*\; \sqrt{2} = 142.27\,V$$

checked

Fig. 4 RMS value of load voltage V_L measured by multimeter.

$$V_{L_{mean}} \; in \; r.m.s. = 86.9 \, V_{rms}$$

$$I_{L_{mean}} \; in \; r.m.s. = V_{L_{mean}} / R_{load} = 86.9/18.8 = 4.62A$$

Results [2.5 Marks]

Parameter	Measurement Value (Unit)
Measured Peak Source Voltage (V_S)	142.27 V
Measured Mean Load Voltage (V_L)	86.9 V_{rms}
Measured Mean Load Current (I_L)	4.62A_{RMS}

Calculation of Theoretical Value [2.5 Marks]

checked

(Include your calculation to obtain the theoretical value of Mean Load Voltage (V_L))
Mean
Since this is a full bridge rectifier, the period of the waveform can be assumed to be π.

Assumptions: Diode is ideal and does not require turn on- voltage

Mean Voltage transferred over to resistor components

$$V_{mean} = \frac{1}{T_{full\ bridge}} \int_0^{\pi} V_{ac,p-p} * \sin(\omega t)\, d\omega t$$

$$V_{mean} = \frac{1}{\pi} \int_0^{\pi} V_{ac,p-p} \sin(\omega t)\, d\omega t$$

$$V_{mean} = \frac{V_{ac,p-p}}{\pi} (-\cos(\omega t)|_0^{\pi}$$

$$V_{mean} = \frac{100\sqrt{2}}{\pi} ((\pi) + \cos(0))$$

$$V_{mean} = \frac{2*100\sqrt{2}}{\pi} = 90.03V$$

Mean Voltage transferred over to load

$$V_{mean,load} = V_{mean} * \left(\frac{18.8}{18.8+0.15}\right) = 90.03 * \frac{18.8}{18.95} V_{mean,load} = 89.32V$$

Mean Voltage transferred over to load

$$I_{mean}, load = \frac{89.32V}{18.8} = 4.75A$$

Waveforms of V_S, V_L, and V_D as one plot [2.5 Marks]

(Include the waveforms of your experimental results from CRO and simulation results from MATLAB/ Simulink or LTSpice)

CRO

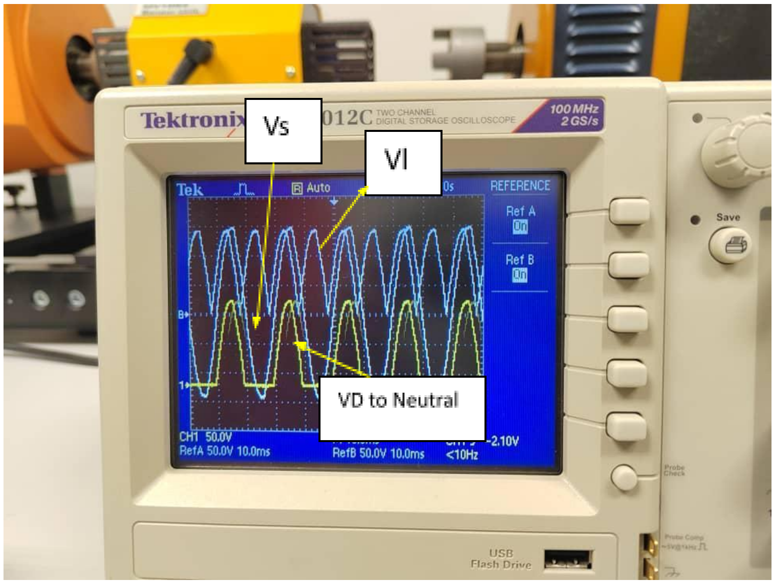

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Fig. 5. Experimental results from CRO, V_S (black), V_D (blue), V_L (Red); y-axis is voltage (V), x-axis is time (ms)

LTSpice

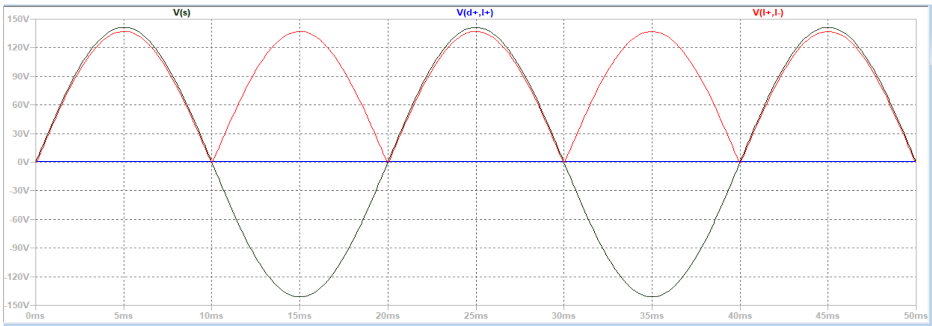

Fig. 6. Simulated waveforms in LTSpice, V_S (black), V_D (blue), V_L (Red); Y axis is voltage (V), X axis is time(ms)

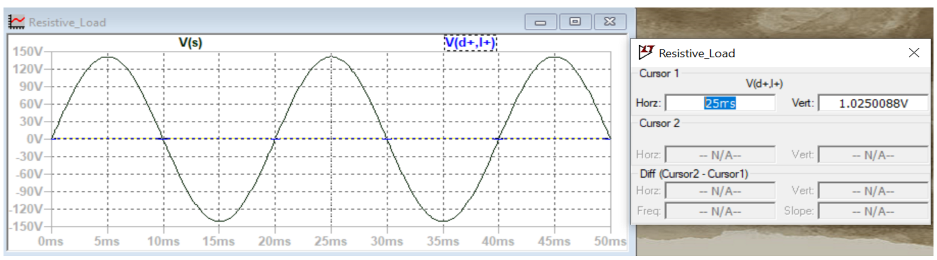

Fig. 7. Simulated waveforms in LTSpice, V_S (black), V_D (blue), with values; Y axis is voltage (V), X axis is time(ms)

Discussion [5 Marks]

(Discuss the waveforms obtained from your experimental and simulation results)

The waveforms displayed in Figure 5 measured by the CRO are analyzed after AC coupling and scaled down, offset on the screen appropriately for comparison purposes. The waveforms have no DC offset after AC coupling. The simulation result matches the experimental results.

The peak of experimental V_S is around 142.27 V, which is approximately the same as the results obtained from simulation, both are sine waves with no phase shift.

In simulation, the load voltage waveform is a fully-rectified sine wave, 137 $V_{p\text{-}p}$. Similarly, the mean voltage across the load, V_L is a fully-rectified sine wave 86.9 V_{RMS}.. The load voltage waveform is fully rectified because four diodes are employed to create a full-wave rectification. During the negative half-cycle of V_S, the current passes through D1 and D4, while during the other cycle the current passes through D2 and D3, effectively rendering the load voltage to take the absolute value of V_S, approximately.

The experimental waveform of V_D is the node V_{D+} to Neutral, this is to avoid the shorting of the diode. However, the simulation of the V_D waveform is very close to 0V, showing a voltage of 1.02V. But as we measured during the experiment, the V_D (experimental) is only 912 mV higher than the load voltage waveform during its peak, otherwise it would look like a straight line if it is not scaled up. The

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micro-voltage level difference is due to the turn-on voltage of the diode. V_D has shown no DC offset due to AC coupling as well.

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2. Resistive – Inductive Load: 18.8 Ω and 250 mH in series

Experimental setup [5 Marks]

(Draw the circuit diagram. State the required measured values and waveforms.)

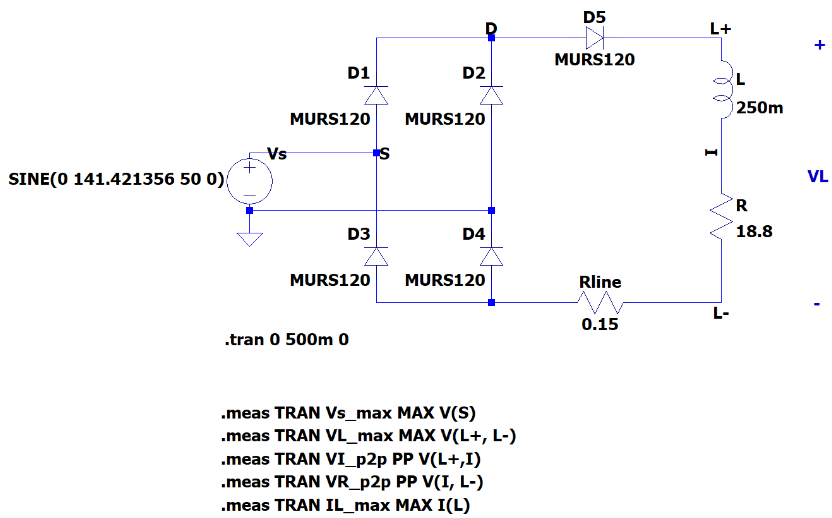
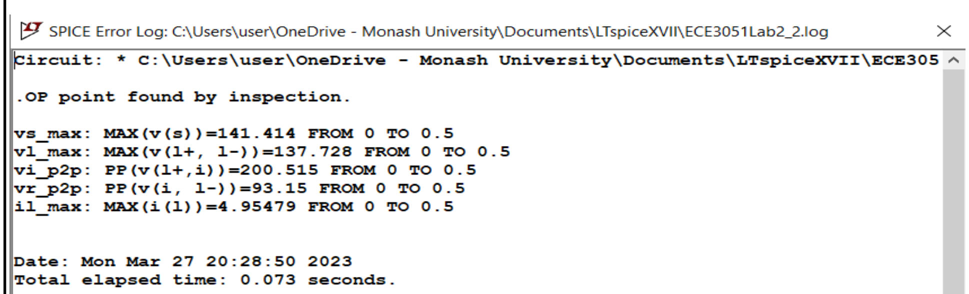


Fig.8 LTSpice Schematic of Resistive and Inductive Load

The required measured values are:
Vs_max - the peak of the source voltage
VL_max - the peak of the voltage across the inductor + 18.8Ω resistor
VI_p2p - the peak-to-peak voltage of the inductor only
VR_p2p - the peak-to-peak voltage of the 18.8Ω resistor only
IL_max - the peak current through the inductor.



```
SPICE Error Log: C:\Users\user\OneDrive - Monash University\Documents\LTspiceXVII\ECE3051Lab2_2.log
Circuit: * C:\Users\user\OneDrive - Monash University\Documents\LTspiceXVII\ECE305

.OP point found by inspection.

vs_max: MAX(v(s))=141.414 FROM 0 TO 0.5
vl_max: MAX(v(l+, l-))=137.728 FROM 0 TO 0.5
vi_p2p: PP(v(l+,i))=200.515 FROM 0 TO 0.5
vr_p2p: PP(v(i, l-))=93.15 FROM 0 TO 0.5
il_max: MAX(i(l))=4.95479 FROM 0 TO 0.5


Date: Mon Mar 27 20:28:50 2023
Total elapsed time: 0.073 seconds.
```

Fig.9 LTSpice Result of Resistive and Inductive Load

Required waveforms are:
Waveform 1: V_s, V_L, I_L
Waveform 2: V_L, V_R and V_I

Waveforms of V_S, V_L and I_L; and V_L, V_R and V_I as one plot [5 Marks]

(Include the waveforms of your experimental results from CRO and simulation results from MATLAB/ Simulink or LTSpice.

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Project the waveforms of VS, VL, and IL in the CRO as one plot.

CRO

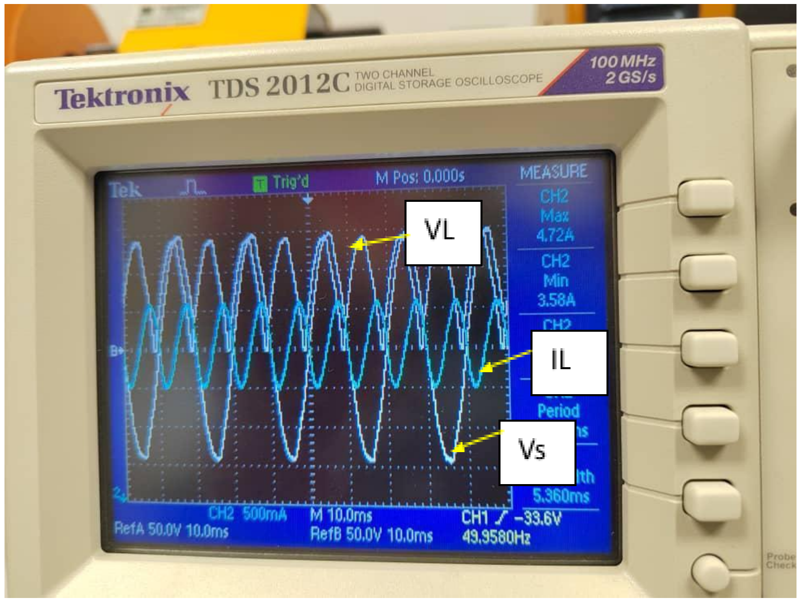

Fig. 10. Experimental results from CRO, V_L (black), V_S, I_L; y-axis is voltage (V) for V_L and V_S and current (A) for I_L, x-axis is time (ms)

LTSpice

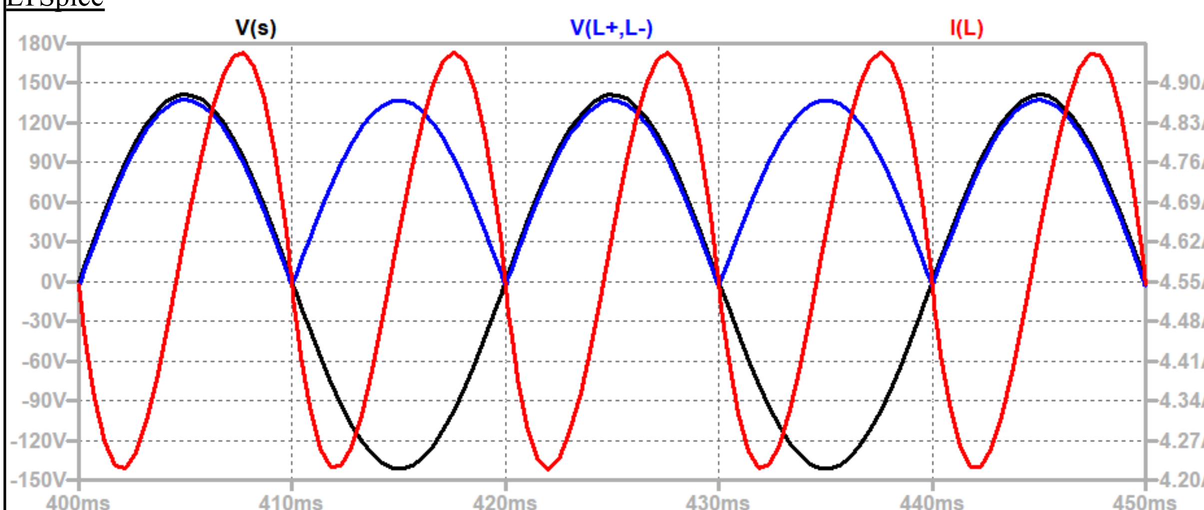

Fig. 11. LTSpice waveforms of V_S (black - voltage (V)), V_L (blue - voltage (V)), and I_L (red - current (A)); x-axis is time (ms)

Project the waveforms of VL, VR, and VI in the CRO as one plot.

CRO

checked

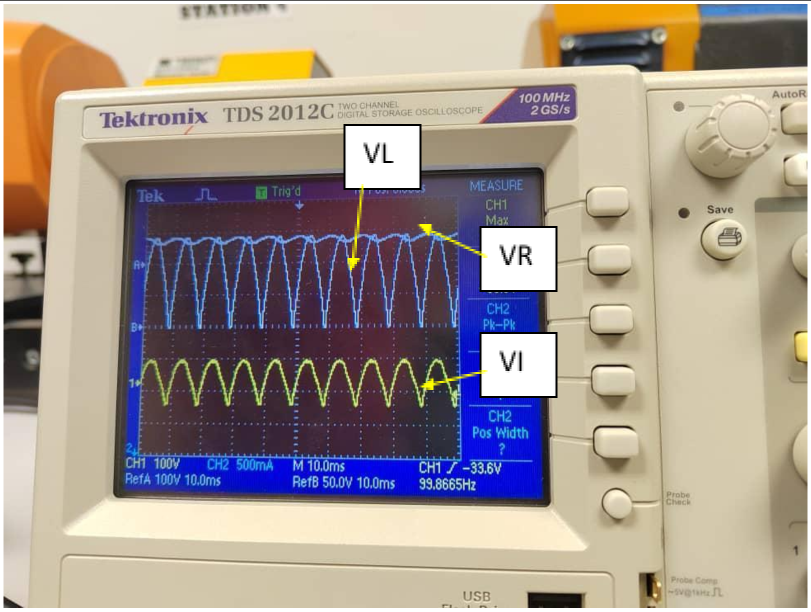

Fig. 12. Experimental results from CRO, V_L, V_S, V_R (yellow); y-axis is voltage (V), x-axis is time (ms)

LTSpice

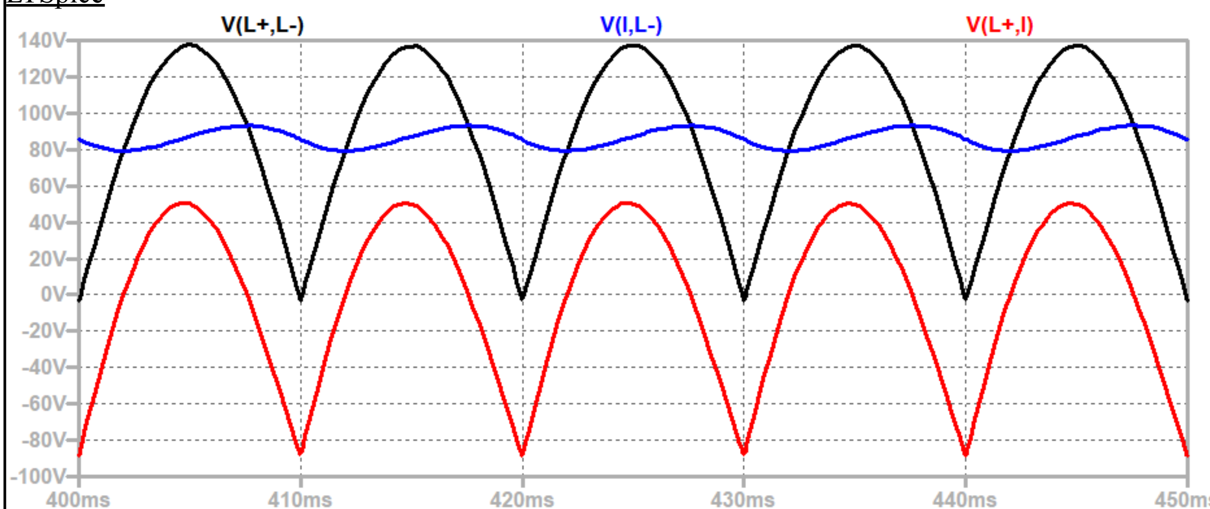

Fig. 13. LTSpice waveforms of V_L (black), V_R (blue), and V_I (red); y-axis is voltage (V), x-axis is time (ms)

Measure the conduction angle

$$conduction\ angle = \frac{t_C}{T_S} \times 360$$

Where t_C is the conduction time (ie. when I_L is positive), and T_S is the period of Vs. According to experimental and simulated results, current through the inductor is always positive, therefore the conduction time is equal to the period of Vs. Therefore, the conduction angle is 360 degrees.

Determine the relationship between V_R, and V_I waveforms at the point where di/dt = 0

di/dt = 0 occurs at the turning points of I_L (max or min), where the gradient is zero. In fig. x, V_L is shown to be very close to zero, while V_R is at its maximum when di/dt = 0. Note that in the

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experimental setup section above, the maximum value of various waveforms have been measured in LTSpice via the .meas function.

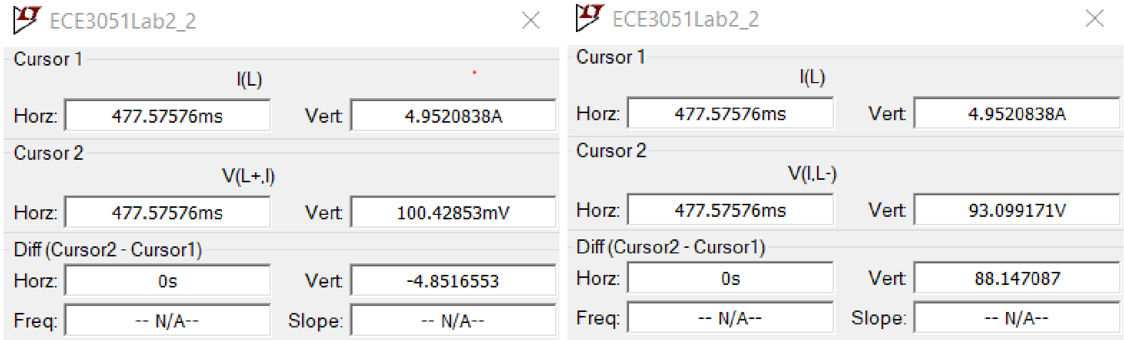

Fig. 14. LTSpice cursor measurements of V_I (Left) and V_R (right) when di/dt = 0

In fig. 15 below, the red dotted lines show where di/dt = 0.

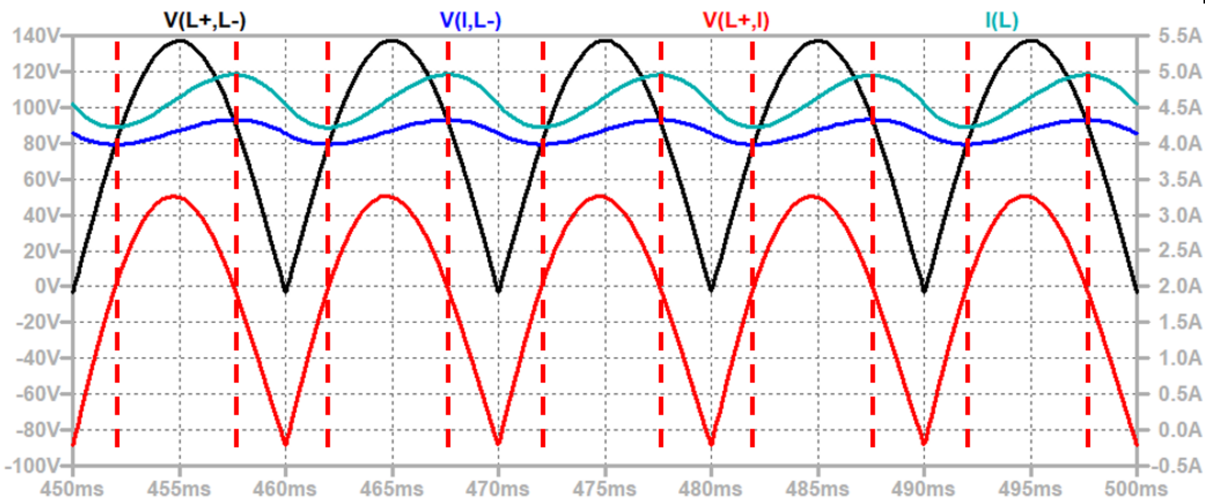

Fig. 15. V_L (black), V_I (red), V_R (blue) waveforms with red dashed lines at di/dt = 0; y-axis is voltage (V) except for I_L current (A), x-axis is time (ms)

The voltage drop across the load is the sum of the voltage drop across the inductor and resistor respectively, given by the equation below.

$$V_L = iR + L\,di/dt$$

When di/dt = 0, all the voltage is dropped across the resistor (ie V_L = iR). The voltage drop across the inductor (V_I = L di/dt) is therefore 0V.

Discussion [5 Marks]

checked

(Discuss the waveforms obtained from your experimental and simulation results)

All waveforms captured by the CRO match the simulations. Note that the CRO waveforms are AC coupled (their DC offset has been removed), and are scaled for easier comparison with the simulation results.

Analysing the waveforms individually:

V_S (Source Voltage)

A sine wave is observed on the CRO. Although the amplitude was not explicitly measured in this question, the voltage reading on the multimeter was 99.1Vrms, which translates to 140.1V peak. Comparing with the ideal 141.42V in the simulation, there were some resistive losses that resulted in a slightly lower value.

V_L (Voltage across the load)

The voltage across the load is a fully rectified sine wave. This is expected since the circuit is a full wave rectifier.

I_L (Current through the load)

It is noticed that the current waveform has twice the frequency as the voltage waveform. This is because a full wave rectifier circuit utilizes both halves of the AC input signal to produce a unidirectional DC output signal. In other words, the output waveform has twice as many peaks as the input waveform, and the current flow in the circuit also changes direction twice as frequently as the input voltage.

V_R (Voltage across the resistor)

A sine wave is observed at the CRO which resembles the shape and magnitude of the simulated waveform. The magnitude is small in comparison with VI because the resistance value is small.

V_I (Voltage across the inductor

A rectified sine wave is observed at the CRO. It is phase shifted approximately 90 deg from VR, this is expected as since the current flowing through the resistor and the inductor is the same, the voltage of the inductor must lag the current waveform by 90 deg.

checked

3. Resistive – Inductive Load: 18.8 Ω and 250 mH in series with FWD

Experimental setup [5 Marks]

(Draw the circuit diagram. State the required measured values and waveforms)

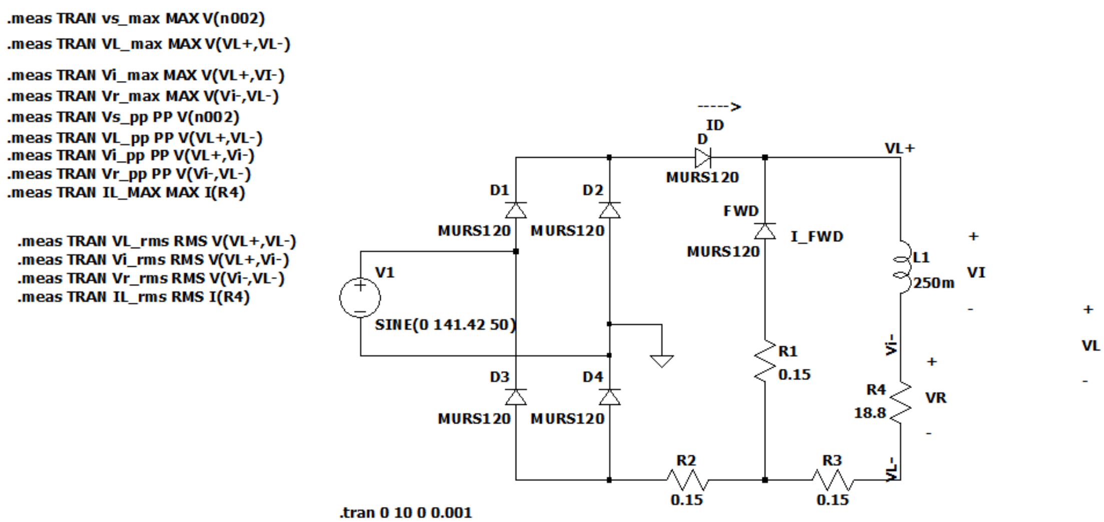

Fig.16. LTSpice Schematic of Resistive and Inductive Load in series with FWD

The measured values are

1. potential difference V_{L+} and V_{L-}, V_L
2. potential difference between the inductor L1, V_I and R4, V_R respectively
3. current across diode D, I_D and FWD, $I_{FWD\text{ and }}I_L$

```
Circuit: * H:\My Drive\ECE3051\Lab 2\Q3.asc

.OP point found by inspection.

vs_max: MAX(v(n002))=141.42 FROM 0 TO 10
vl_max: MAX(v(vl+,vl-))=137.781 FROM 0 TO 10
vi_max: MAX(v(vl+,vi-))=111.959 FROM 0 TO 10
vr_max: MAX(v(vi-,vl-))=91.7434 FROM 0 TO 10

vs_pp: PP(v(n002))=282.84 FROM 0 TO 10
vl_pp: PP(v(vl+,vl-))=140.065 FROM 0 TO 10
vi_pp: PP(v(vl+,vi-))=198.799 FROM 0 TO 10
vr_pp: PP(v(vi-,vl-))=91.7434 FROM 0 TO 10

il_max: MAX(i(r4))=2.78265e-010 FROM 0 TO 10

vl_rms: RMS(v(vl+,vl-))=94.4307 FROM 0 TO 10
vi_rms: RMS(v(vl+,vi-))=42.7068 FROM 0 TO 10
vr_rms: RMS(v(vi-,vl-))=85.3548 FROM 0 TO 10
il_rms: RMS(i(r4))=4.54015 FROM 0 TO 10
```

Fig.17. LTSpice Results of Resistive and Inductive Load in series with FWD

Required waveforms are:
Waveform 1: $V_{L,}$ $V_{I,}$ V_R
Waveform 21: $V_{L,}$ $I_{D,}$ I_{FWD}
Waveform 3: I_D I_{FWD} I_L

checked

Waveforms of V_L, V_R and V_I; V_L, I_D and I_{FWD}; and I_D, I_{FWD} and I_L as one plot [5 Marks]

(Include the waveforms of your experimental results from CRO and simulation results from MATLAB/ Simulink or LTSpice. Determine how all three currents are related to each other.)

CRO

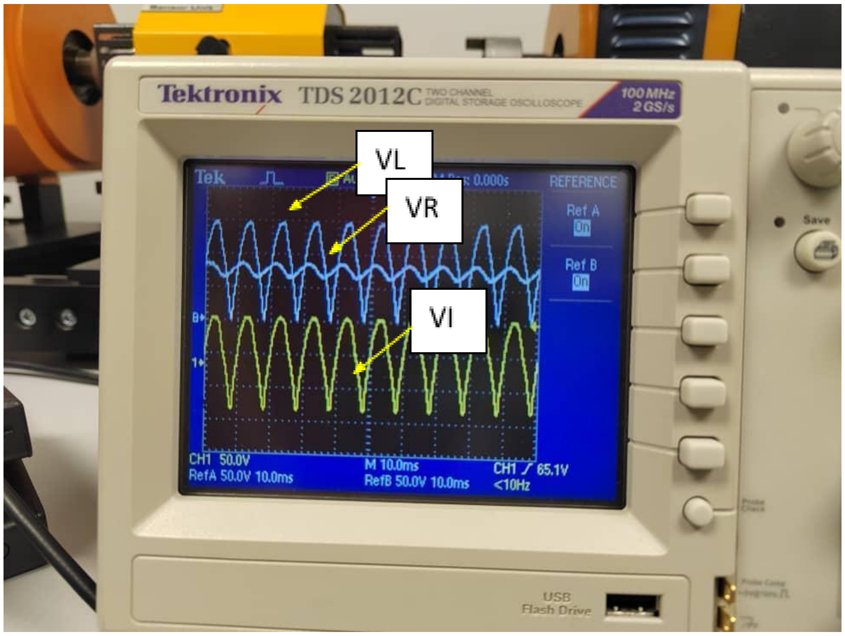

Fig. 18. Experimental results from CRO, V_L, V_S, V_I (yellow); y-axis is voltage (V), x-axis is time (ms)

LTSpice

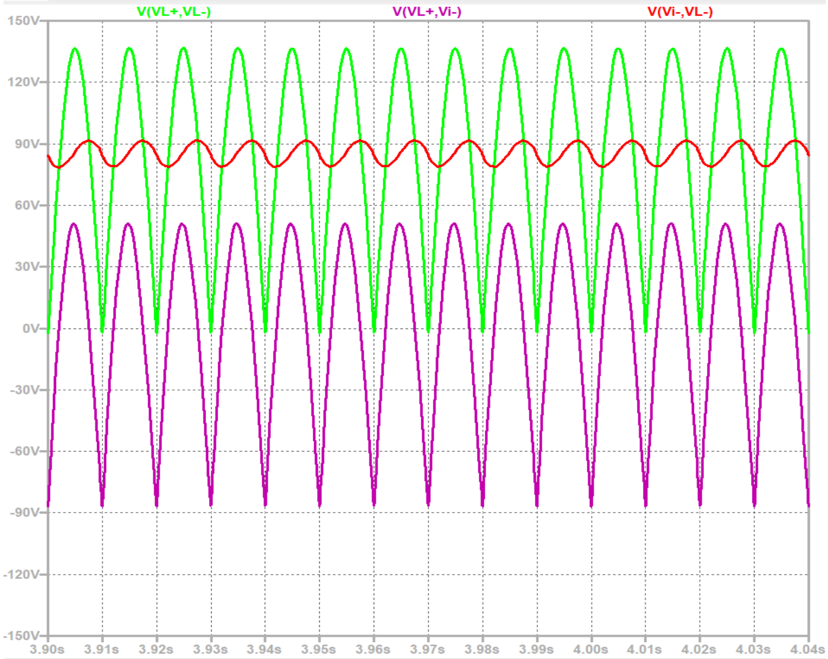

Fig. 19. LTSpice waveforms of $V_{L\ (Green)}$, $V_{I\ (Purple)}$, $V_{R\ (red)}$

CRO

checked

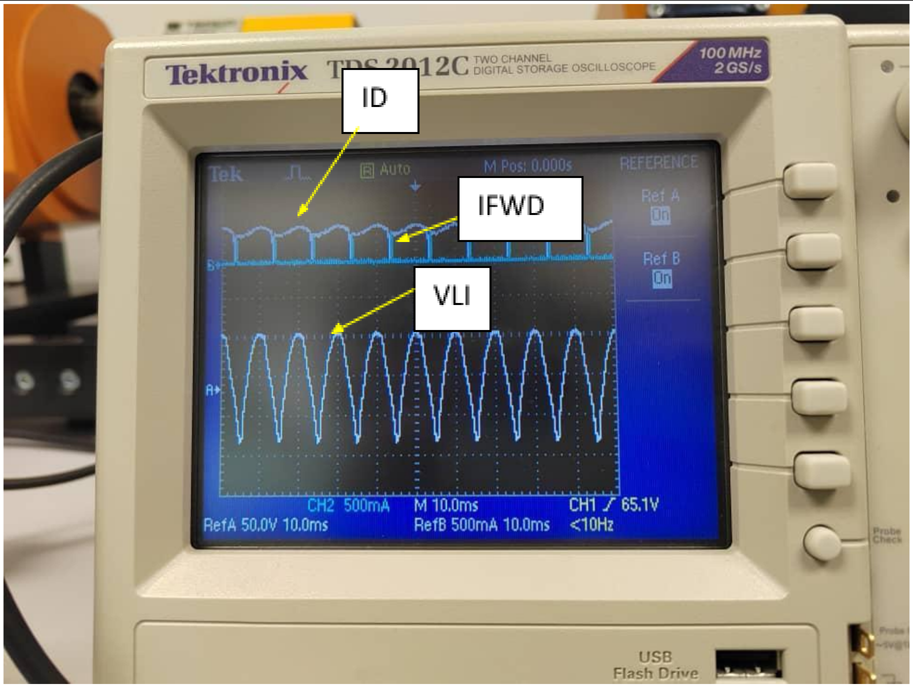

Fig. 18. Experimental results from CRO, I_D, I_{FWD}, V_{LI} ; y-axis is voltage (V_{LI}) and current (A) for I_D, I_{FWD}, x-axis is time (ms)

LTSpice

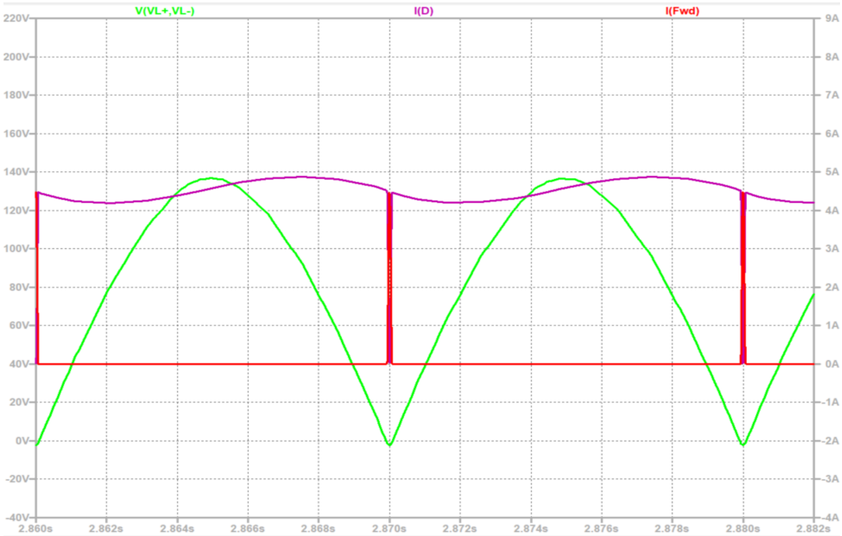

Fig. 19. LTSpice waveforms of $V_{L\ (Green)}$, $I_{D\ (Purple)}$, $I_{FWD\ \mathbf{(Red)}}$, y-axis is voltage (V_{LI}) and current (A) for I_D, I_{FWD}, x-axis is time (ms)

checked

CRO

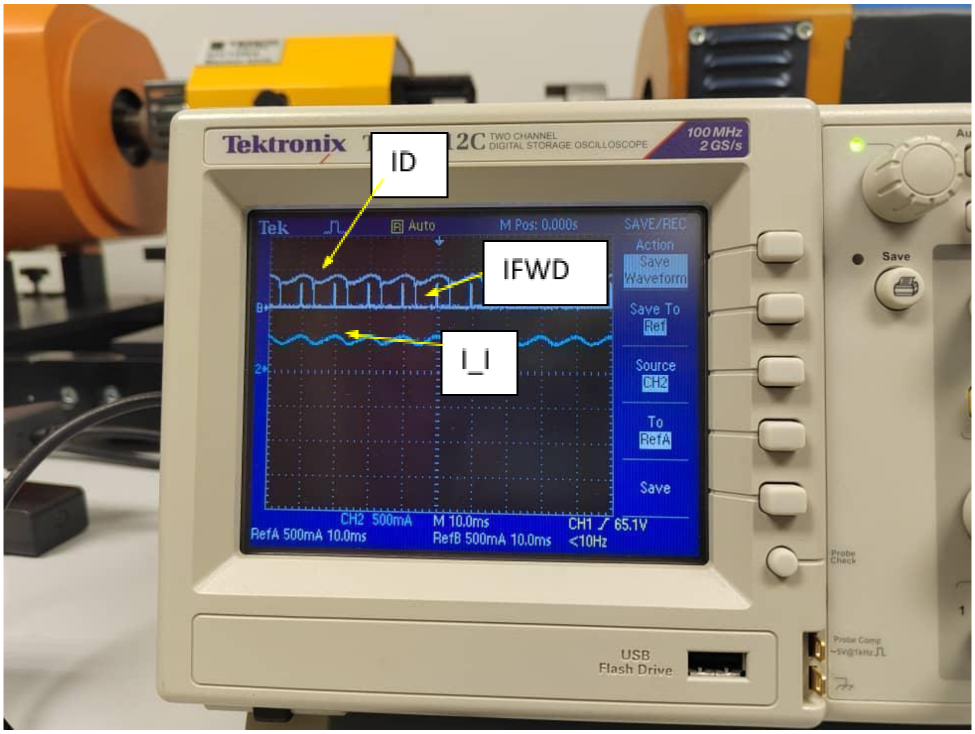

Fig. 20. Experimental results from CRO, I_D, I_{FWD}, I_I ; y-axis is current (A), x-axis is time (ms)

LTSpice

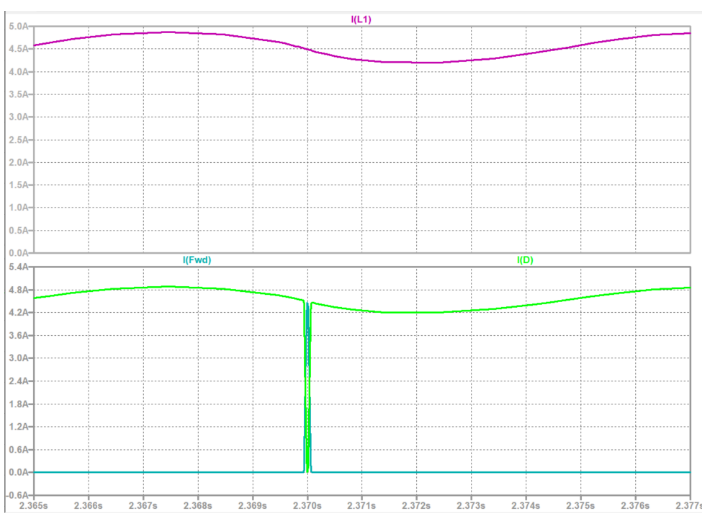

Fig. 21. LTSpice waveforms I_D, I_{FWD}, I_I ; y-axis is current (A), x-axis is time (ms)

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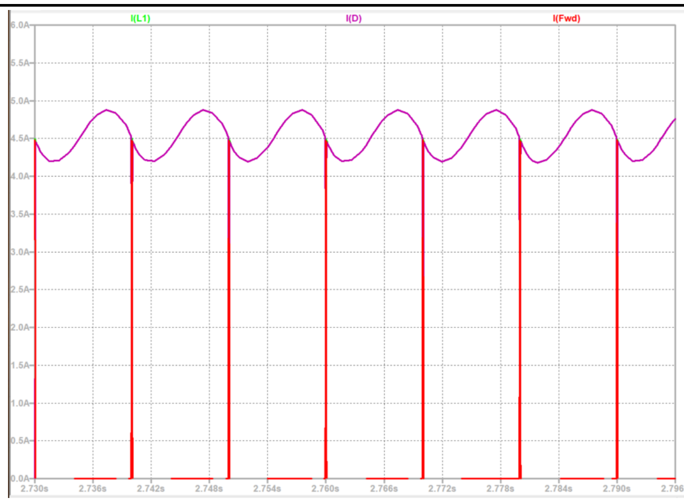

Fig. 22. LTSpice waveforms of $I_{D\text{ (Green)}}$, $I_{FWD\text{ (Turquoise)}}$, $I_{l\text{ (Purple) (Zoomed In)}}$/ $I_{D\text{ (Purple)}}$, $I_{FWD\text{ (Red)}}$, $I_{L\text{(Green) (Zoomed out)}}$; y-axis is current (A), x-axis is time (ms)

Determine how all three currents are related to each other.

The currents are related by Kirchoff's Law on the Conservation of Current

We can see that $I_{FWD} + I_D = I_L$

Discussion [5 Marks]

(Discuss the waveforms obtained from your experimental and simulation results)

It can be observed that the resistor voltage is getting a small ripple voltage around 90V, whereas the inductor voltage follows the rectified voltage shape closely. If we were to add the inductor voltage and resistor voltage, we would obtain the exact voltage given by VL, which obeys Kirchhoff's Voltage Law. The presence of the inductor and the full bridge rectifier was able to regulate the load voltage at approximately 90V.

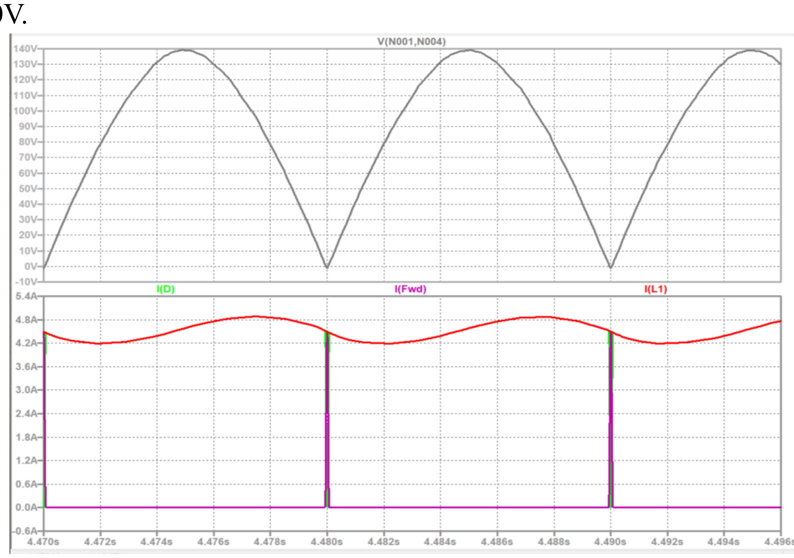

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Fig. 23. LTSpice waveforms of V_L (first waveform on top) y-axis is voltage (V), x-axis is time (ms), , $I_{D\ (Green)}$, $I_{L1\ (Red)}$, $I_{FWD\ (Blue)}$; y-axis is current (A), x-axis is time (ms)

For the current waveform, the explanations can be divided into when Diode D is forward biased and reverse biased. Diode D will be forward biased, when the supply voltage exceeds the turn-on voltage of the diode, and will be in reverse biased when the rectified supply voltage is below the turn on voltage of Diode D.

When Diode D is forward biased, the branch with the Free-Wheeling Diode can be disregarded as the FWD is now in reverse bias. The current waveform across the load resistor and inductor, I_L should follow the shape of the resistor voltage, based on Ohm's Law and the branch being in series. I_D should also be identical to I_L due to Kirchhoff's Current Law.

When Diode D is in reverse biased, the FWD will then become forward active, allowing current flow, which explains the drop in current across Diode D and the increase in current of the FWD, which is due to the energy supply from the inductor. However, as this is a Full Bridge Rectifier, Diode D will be in forward biased in the next half cycle. The spikes of the current flow in both the diode current and FWD current is due to the momentary switching of current flow.

checked

4. Resistive Load: 18.8 Ω with Output Capacitor

Experimental setup [5 Marks]

Draw the circuit diagram. State the required measured values and waveforms.)

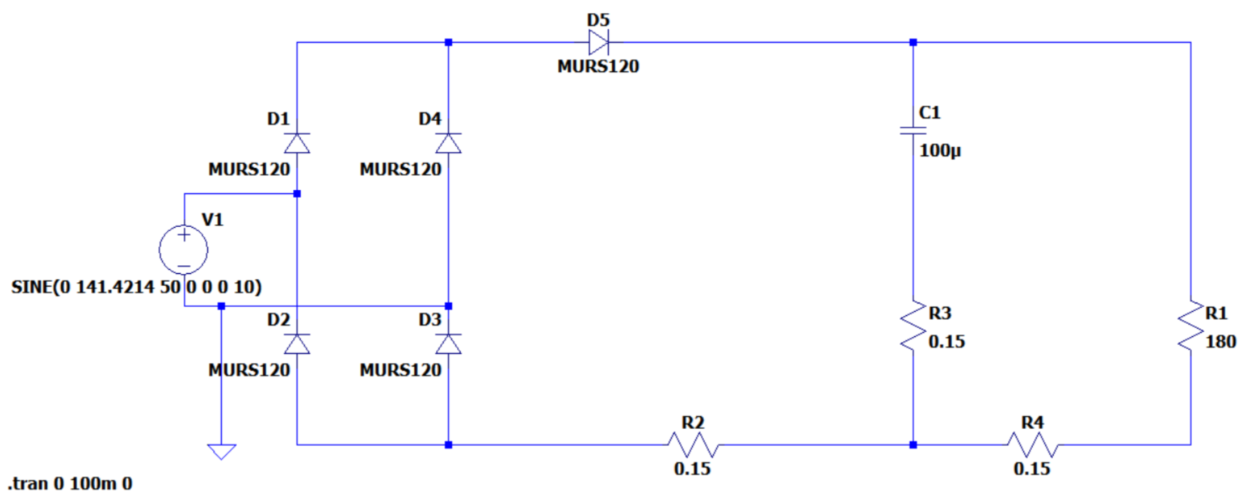

Fig.24. LTSpice Schematic of Resistive and Capacitive Load

The required measurements are

1. the source voltage waveform (Vs)
2. the load voltage waveform (V_L)
3. and the voltage across the rectifying diode (V_D).
4. We also need to determine the voltage ripple in the load voltage

The required waveform is

Waveform 1: Vs (The source voltage waveform), V_L (The load voltage waveform), V_D (the voltage across the rectifying diode).

Waveforms of V_S, V_L and V_D; V_S and V_L; as one plot [5 Marks]

(Include the waveforms of your experimental results from CRO and simulation results from MATLAB/ Simulink or LTSpice. Determine the voltage ripple in the load voltage. Set the resistance of the resistive load to the maximum value. Explain how this ripple voltage changes with the new load)

<u>CRO</u>

When RL = 18.8 Ohm

checked

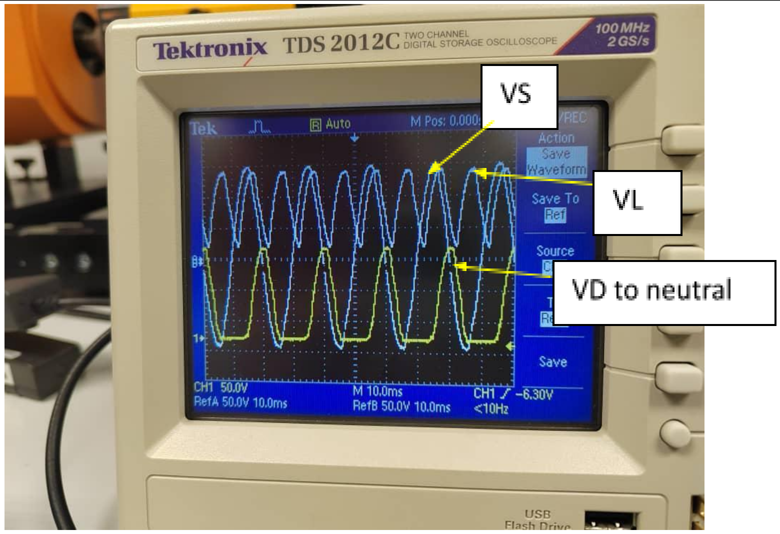

Fig. 25. Experimental results from CRO, V_S, V_L, V_D (to neutral to avoid short circuit) ; y-axis is Voltage (V), x-axis is time (ms)

LTSpice

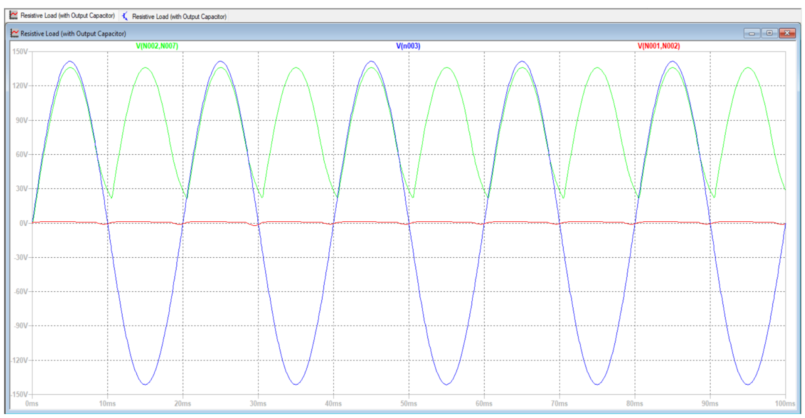

Fig. 26. LTSpice waveforms V_S (Blue), V_L (Green), V_D (Red) ; y-axis is voltage (V), x-axis is time (ms)

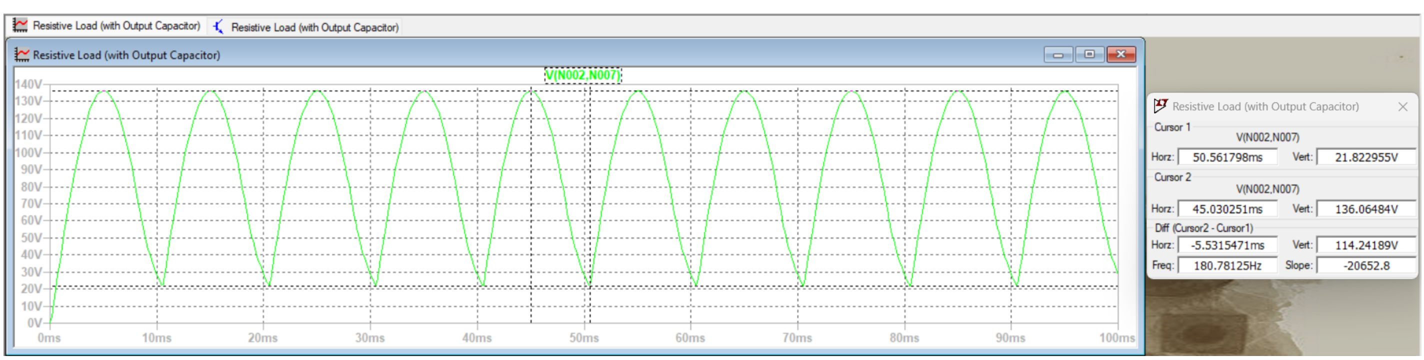

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Fig. 27. LTSpice waveforms V_S (Blue), V_L (Green), V_D (Red) ; y-axis is voltage (V), x-axis is time (ms); with measurements taken

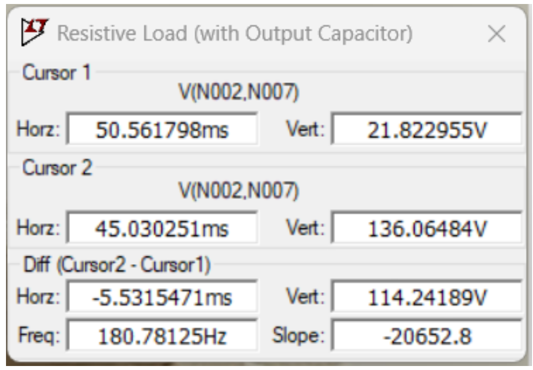

Fig. 28. LTSpice waveforms V_S (Blue), V_L (Green), V_D (Red) ; y-axis is voltage (V), x-axis is time (ms); with measurements taken (zoom in)

CRO

When RL = 180 Ohm

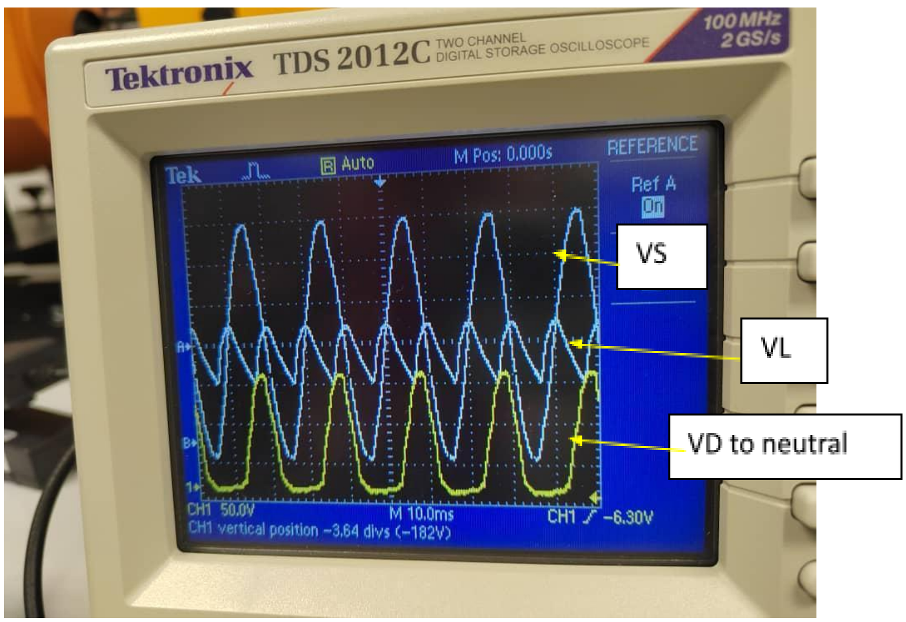

Fig. 29. Experimental results from CRO, V_S, V_L, V_D (to neutral to avoid short circuit) ; y-axis is Voltage (V), x-axis is time (ms); maximum resistance load

LTSpice

checked

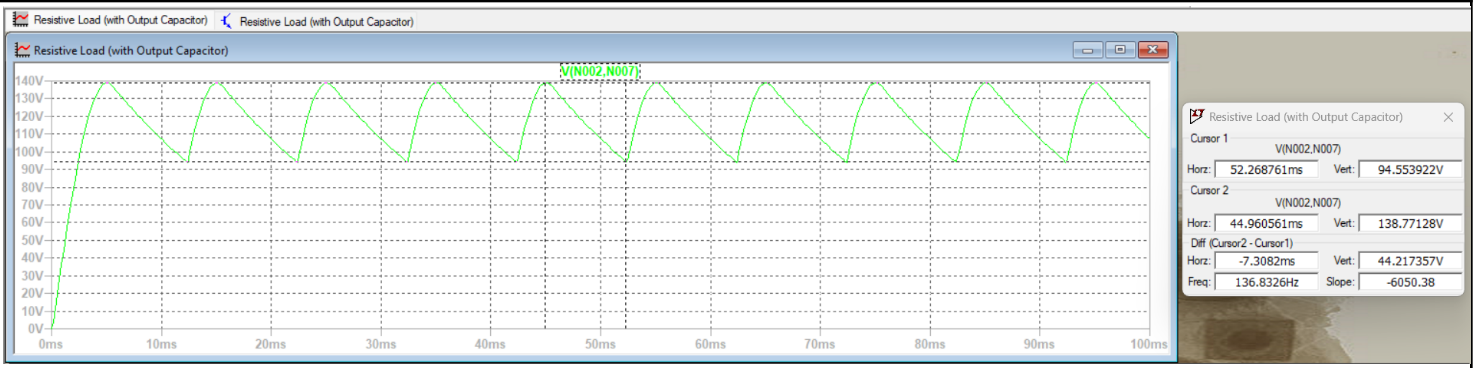

Fig. 30. LTSpice waveforms V_S (Blue), V_L (Green), V_D (Red) ; y-axis is voltage (V), x-axis is time (ms); with measurements taken; maximum resistance load

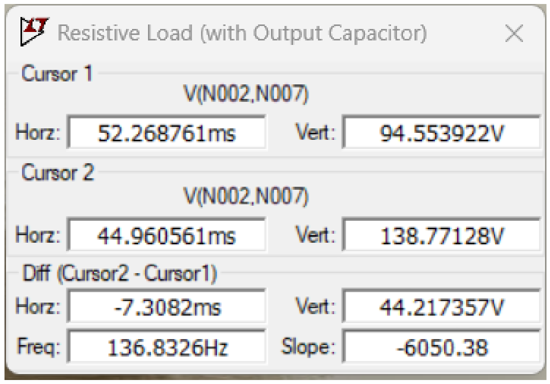

Fig. 31. LTSpice waveforms V_S (Blue), V_L (Green), V_D (Red) ; y-axis is voltage (V), x-axis is time (ms); with measurements taken; maximum resistance load (Zoom in)

Based on the measured simulated values, we can make our deduction about the voltage ripple in the load voltage

When RL is 18.8Ω

$\min(VL, 18.8\Omega) = 21.822955\text{V}$
$\max(VL, 18.8\Omega) = 136.0648\text{V}$
$VL, ripple, 18.8\Omega = \max(VL, 18.8\Omega) - \min(VL, 18.8\Omega) = 114.241845\text{V}$

When RL is 180Ω

$\min(VL, 180\Omega) = 94.553922\text{V}$
$\max(VL, 180\Omega) = 138.77128\text{V}$
$VL, ripple, 180\Omega = \max(VL, 180\Omega) - \min(VL, 180\Omega) = 44.217358\text{V}$

As we can see from the above calculated values, we can deduce that as the resistance of the load increases, the voltage ripple in the load voltage will decrease.

Discussion [5 Marks]

(Discuss the waveforms obtained from your experimental and simulation results)
The waveforms of VS, VD and VL from the experimental results and simulation results **should be similar**.

checked

As we can see from the above simulated and experimental graph, Vs is a full sine wave and VL is a fully rectified wave that has different rise and fall time. The reason for the waveform shape of VL is due to the discharge of the 100 µF capacitor. The discharge of the capacitor is an exponential decay which would result in the waveform shown above.

VD is also a rectified wave. The reason for the small voltage is because the voltage required for the diode to conduct is small. We can also deduce that as the load resistance increases, the voltage ripple decreases, but the maximum and minimum values of the load voltage increase. The voltage ripple becomes more apparent too.

We can explain this phenomenon by looking at the capacitor. As the capacitor starts to accumulate energy (electric field), the voltage at the positive terminal of the diode, D will become lower and the voltage at the negative terminal of the diode, D will increase when the source voltage, Vs starts to decrease from its maximum value. Diode D will become reverse biased and this would cut off (disconnect) the load from the source.

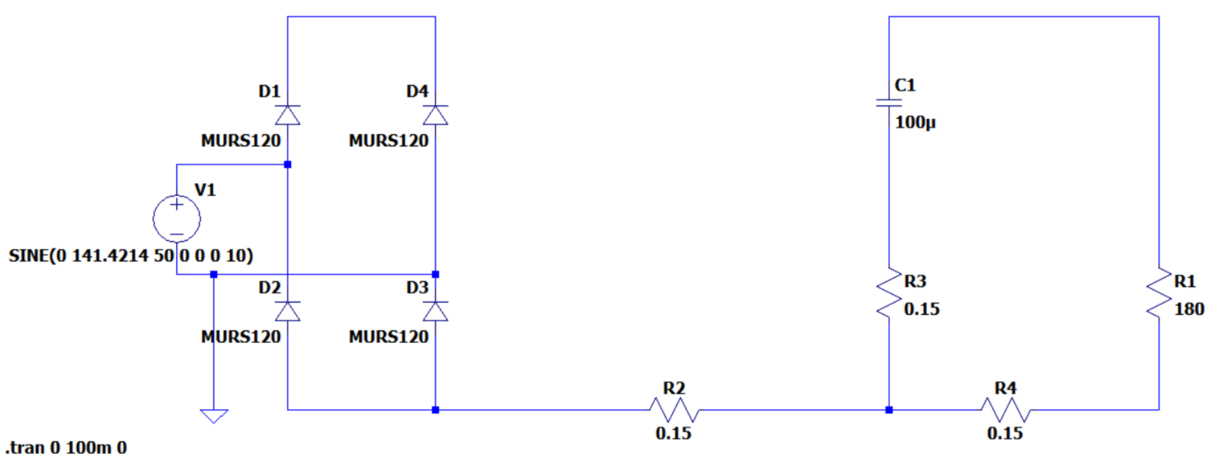

Fig. 32. LTSpice Schematic of Resistive and Capacitive Load, diode in reverse bias

When Vs starts to decrease from its maximum value to the value of the rectified voltage, the rectified voltage, Vrec, will be larger than the voltage across the load, VL. The capacitor will discharge and will act as the energy source of the load.

The current flowing through the diode D will be 0. This means that the current flowing through C1, R3 and R1 is zero as well.

$$-\frac{V_L}{R_L} = C\frac{dV_C}{dt}$$

$$V_L = -R_L C\frac{dV_C}{dt}$$

We can deduce from the above equation that the time constant is RLC and is directly proportional to RL which explains why the capacitor takes some time to discharge when the resistance of the load increases. This explains why as the resistance of the load increases, we will have a smaller ripple voltage.

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General Discussion

1. List four main differences between a full-wave and a half-wave diode rectifier circuit. State the difference in terms of efficiency for both the full-wave and half-wave diode rectifier circuit. [10 Marks]

Difference 1:
Full-wave rectification rectifies the negative component of the input voltage to a positive voltage (thus converting it into DC using a diode bridge configuration. This means the full bridge is bidirectional in nature as it allows current to flow in 2 directions in the supply (1 direction in the load)
Half-wave just removes the negative voltage component, thus only allowing current flow in one direction of the AC supply [1]
The waveforms of both configurations are shown below

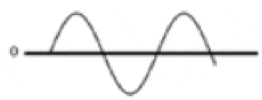

Fig. 33. Input waveform

Fig. 34. voltage waveform after rectification (full bridge)

Fig. 35. voltage waveform after rectification (half bridge)

Difference 2:
A full wave rectifier uses up to 2 (center tapped)-4(bridge) diodes to perform the full rectification. Conversely, a half wave rectifier only uses 1 diode to ensure current flows in one direction.

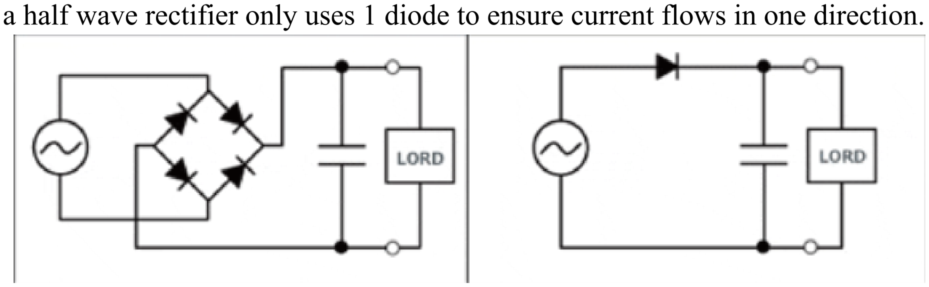

Fig. 36. (left) Full-wave rectification; (right) Half-wave rectification

Difference 3:
The output frequency of the full wave rectification is double of the supply voltage frequency due to the full rectification allowing it to be continuous. The output frequency of the half wave frequency is the same as the supply voltage frequency. [2]
Difference 4:
The peak inverse voltage for the half wave rectifier is equal to the maximum value of the input voltage. For the full wave rectifier, the peak inverse voltage is equal to the double of the maximum value of input voltage [2]

checked

Difference in efficiency
Efficiency of a rectifier circuit is determined as the ratio of DC output power to the AC input power. For a half-wave rectifier, rectifier efficiency is 40.6%. For a full-bridge rectifier, efficiency is 81.12% [3]

2. Explain why ripple voltage appears during half-wave and full-wave rectification. Suggest an effective method to reduce the ripple voltage in a rectifier circuit. [10 Marks]

Ripple is the residual periodic variation in the DC voltage that was rectified from an AC voltage supply. The ripple is due to incomplete suppression of the AC voltage after rectification through the use of voltage smoothing circuits like capacitor smoothing or free-wheeling diodes. [4]

Ripple may be undesirable due to the following issues:
Ripple will cause heating in DC circuits when applied to components with parasitic capacitance.
The presence of ripple can also reduce the resolution of digital circuits, causing logic circuits to give incorrect outputs

An effective method to reduce ripple voltage in a rectifier circuit is to a smoothing capacitor to the circuit.
Based on [5], the peak-to-peak voltage of the ripple voltage is given in the form

$$V_{pp} = \frac{I_{output}}{2 * frequency * capacitance}$$

Thus, if we can add a high capacitance capacitor to the circuit, it will be able to smoothen the output voltage waveform and reduce the ripple voltage. However, there are some tradeoffs, such as increase in reactive power than could increase the apparent power consumption of the circuit. We can also employ a low-pass filter by calculating the frequency of the ripple and designing a low pass filter with the ripple voltage frequency as the cut off frequency. [5]

Conclusion and Findings [14 Marks]

(Include your analysis of the behavior of a single phase full-wave rectifier circuit. State the learning outcomes of this experiment.)

In a nutshell, the results obtained from the experiments have given us a better understanding in the workings of a full-wave rectifier and the implementation of the different types of loads and its effect on the result for both the simulation that we did in Simulink/LTspice and the experiment that we did in the lab. We also have to learn how to use multiple physical equipment in the laboratory such as the clamp meter and oscilloscope. The clamp meter is used to measure power, RMS current and voltage while the oscilloscope is used to plot the current and voltage waveform that we require.

Resistive Load:
As we can see from the above graphs from the LTspice simulation and oscilloscope, the waveforms plotted are very similar to each other. The measured value and the theoretical value will be slightly different from each other as the theoretical value does not take into account the resistivity of the wire. We can also see that there will be no phase shift for the input and output voltage (Vs and VL) as this is a resistive load (absence of capacitor and inductor).

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We can also observe that the full cycle of the voltage source will be rectified. During the positive half-cycle of Vs, the current will flow through diodes D1 and D4. During the negative half-cycle of Vs, the current will flow through diodes D2 and D3. We will obtain a simple rectifier circuit.

Resistive - Inductive Load:
As we can see from the above graphs from the LTspice simulation and oscilloscope, the waveforms plotted are also very similar to each other. The working principle of this rectifier circuit is also very similar to the circuit in Question 1. The only difference between the two rectifier circuits is the addition of an inductor in the rectifier circuit of Question 2. The inductor will smooth the output voltage as it stores energy (when the diode is forward-biased) and releases energy to the load (when the diode is reversed-biased).

We can also note that the waveform that we have obtained in the oscilloscope has an inductive flyback but the waveform in the simulation does not have it. The reasoning behind this observation is that the inductor is assumed to be ideal in the simulation. When power is removed from the inductor, it will be changed immediately (instantaneous). The VL value is also lower in the hands-on experiment. The voltage drop across the diode will cause the amplitude to be different when compared to the voltage source.

Resistive - Inductive Load with FWD:
As we can see from the above graphs from the LTspice simulation and oscilloscope, the waveforms plotted are also very similar to each other. A FWD (Free Wheeling Diode) has been introduced in this circuit in addition with two 0.15Ω resistor. The FWD will only allow the circuit to conduct when the magnitude of the rectified voltage is smaller than the turn-on voltage of the diode. This will cause the change in the load current to be smaller as the load current will only oscillate at a small amplitude. This will allow the load to operate consistently even at high frequencies as this would prevent large current oscillations from occurring which would protect the load.

When the load voltage is negative, the IFWD will be an upward spike and Id will have a downward spike. The inductor stores and releases energy, allowing the free-wheeling diode to start conducting current in a brief period of time while other diodes will stop conducting, resulting in the production of spikes. Since the sum of Id and IFWD will equate to the load current, IL, ID will become IL, with downward spikes whenever the load voltage is negative (Inductor Charging and Discharging). IFWD will add up to ID, eliminating load current spikes, resulting in a sinusoidal wave.

Resistive Load with Output Capacitor:
As we can see from the above graphs from the LTspice simulation and oscilloscope, the waveforms plotted are also very similar to each other. A capacitor will replace the FWD (Free Wheeling Diode) and the inductor in the circuit.The capacitor will smoothen the output voltage as it discharges when the diode D is in reverse-bias.VD and VL will be rectified waves due to the rectification made by the diodes. The 100µF capacitor will cause the exponential decay of the waveform for VL and VD. We can also conclude that when the load resistance increases, the voltage ripple will decrease and the maximum and minimum voltage increases.

In the general discussion section, we have briefly discussed the difference between a half-wave rectifier and a full-wave rectifier. The reasoning behind the existence of the ripple voltage and the methods to reduce the ripple voltage in the rectifier circuit has also been discussed.

In conclusion, we have learned a lot in this lab experiment such as how different rectifier circuit configurations functions and achieved the objectives of this lab which is to examine the behavior of single phase diode circuits.

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References (Minimum 3 References) [6 Marks]

[1] "Full-Wave Rectification and Half-Wave Rectification | Electronics Basics | ROHM," www.rohm.com. https://www.rohm.com/electronics-basics/ac-dc/rectification#:~:text=Full%2Dwave%20rectification%20rectifies%20the

[2] "Difference between Half Wave and Full Wave Rectifier," www.tutorialspoint.com. https://www.tutorialspoint.com/difference-between-half-wave-and-full-wave-rectifier

[3] "Diode As A Rectifier - Half Wave Rectifier & Full Wave Rectifier," BYJUS. https://byjus.com/physics/how-diodes-work-as-a-rectifier/#:~:text=The%20rectifier%20efficiency%20of%20a%20full%2Dwave%20rectifier%20is%2081.2%25. (accessed Mar. 25, 2023).

[4] "Ripple (electrical)," Wikipedia, Jun. 18, 2022. https://en.wikipedia.org/wiki/Ripple_(electrical)#:~:text=Ripple%20(specifically%20ripple%20voltage)%20in

[5] "How do you reduce voltage ripple?," Coil Technology Corporation, Jul. 02, 2020. https://www.powerctc.com/en/node/4569

******** THE END *******

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MONASH University MALAYSIA

SCHOOL OF ENGINEERING

ELECTRICAL AND COMPUTER SYSTEMS ENGINEERING

LABORATORY REPORT MARKING RUBRIC

ECE3051: ELECTRICAL ENERGY SYSTEMS

Experiment Number: 3

Title of Lab Sheet: AC Induction Motor & Drive System

Group Number: 8

No.	Student ID	Name of Group Members	Total Marks
1	30720230	Loh Jia Quan	98/100
2	31106889	Agill Kumar Saravanan	98/100
3	30719305	Huan Meng Hui	98/100
4	32194471	Tan Jin Chun	98/100
5	32259417	Chong Yen juin	98/100

MARKS BREAKDOWN

Section	Total Score	Actual Marks	Scoring Band	Criteria	Comment
Results	40		30-40	Clear and completely labelled figures of the experiment/simulation results with justifications and tables. A detailed caption is provided for each figure with an in-text figure reference. The x-axis and y-axis are labelled with the unit in the bracket. The legend is provided whenever it is deemed to be required. If there is more than one line, the lines should be clearly distinguishable with the visible difference such as dotted line, dashed line and solid line, even in black and white.	40
			20-30	Some of the figures of the experiment/simulation setup are not clear, do not have any labelling/ caption/ in-text caption reference/ distinguishable multiple lines and are blurry. The table and justification have mistakes or errors.	
			0-20	Insufficient amounts of figures and labelling of the experiment/simulation layout setup, which is not correct and/or unclear. The table is not filled.	
Discussion	40		30-40	Complete data collection and presentation using tables/figures/ graphs with appropriate labels. Discussion of the results with prudent judgment. Have a comparison of the measured results with theoretical values and in-text citations from the peer-reviewed references. The comprehensive comparison, evaluation and justification of the results are given with clear explanation to demonstrate the understanding of the laboratory.	40
			20-30	The discussion shows little understanding of what the experiment/simulation is all about. Brief comparison, evaluation and justification of the results, with unclear/ incorrect explanation on the theoretical and experimental/ simulation results.	
			0-20	Only restatement of the results without commenting on the expected key points. Incorrect judgment/ arguments were used. No comparison, evaluation and justification of the results, with an unsatisfactory explanation on	

				the theoretical and experimental/ simulation results.	
Conclusion, References and Appendix	20		15-20	Explained how the aims of the experiment have been achieved. The key features of the methods used, the most important results and the findings of the laboratory have been summarized. Complete references list to any book, articles and websites is provided with proper in-text citations in correct formatting. The appendix is provided in detail.	18
			10-15	A conclusion is drawn but is not supported by the experimental/ simulation evidence and a clear understanding of the findings. Incomplete references to the books or any other sources used in the report and the in-text citations are inappropriate or incorrect. The appendix is partially provided.	
			0-10	No sensible conclusion. The referencing is presented in the wrong format. No evidence, attachments, appendices are attached. Irrelevant referencing was used. Unclear understanding of the experiment without a summarized conclusion and the evidence of results. No appendix is provided.	
Total	100				98

Examiner/ Assessor of ECE3051: Electrical Energy Systems

Date: 19/4/2023

EXPERIMENT 3

AC INDUCTION MOTORS AND DRIVE SYSTEMS

1. Preliminary

Nameplate data for the induction and dc motors [4 Marks]

(Insert a picture of the nameplate data for both the induction and dc motors. Alternatively, you may insert a data table in writing)

Fig. 1. Nameplate data for the induction machine.

Fig. 2. Nameplate data for the DC machine.

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Experimental setup [8 Marks]

(Insert a picture of your actual experimental setup and label the equipment used.)

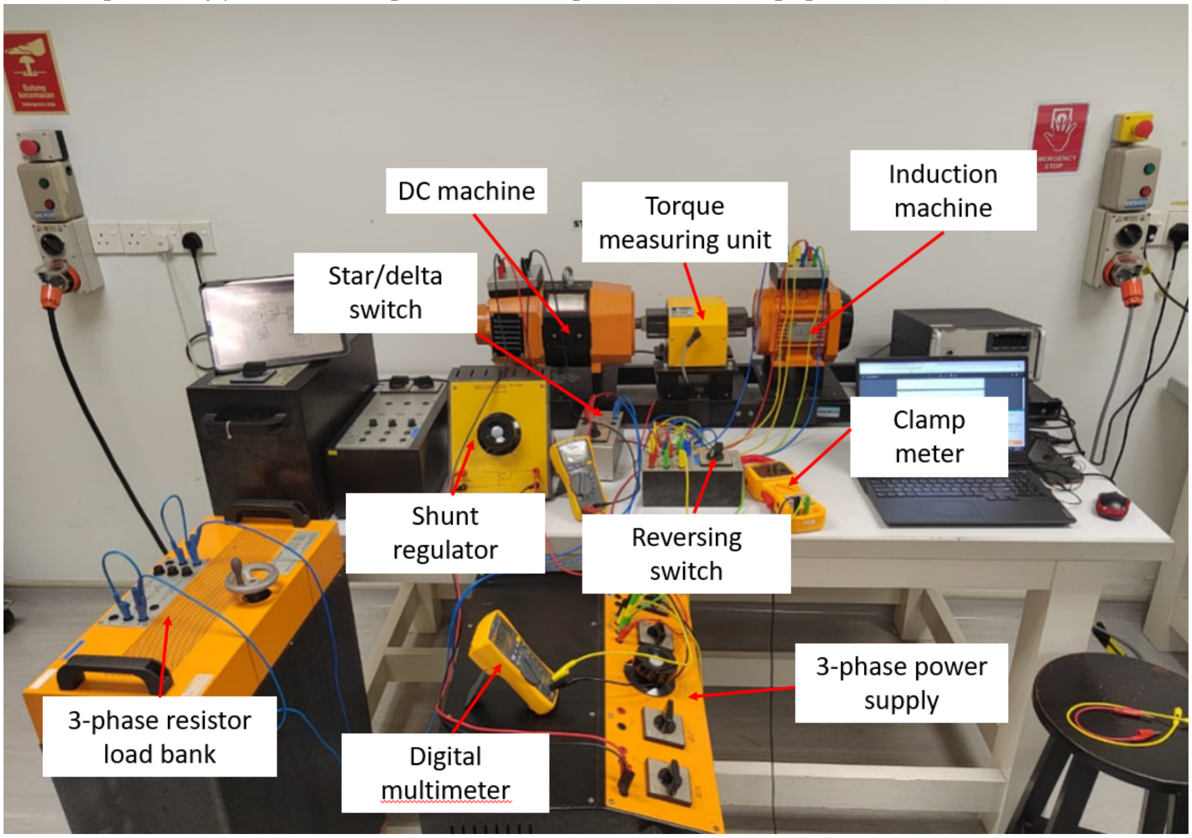

Fig. 3. Experimental setup in the lab with equipment labeling.

Fig. 4. Torque measuring unit display in lab

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Equivalent circuit parameters and torque-speed characteristic

Locked-rotor test results [8 Marks]

Measurements	Value (Unit)
Stator voltage, V	$29.75V_{RMS}$
Stator current, I	$4.46A_{RMS}$
Input real power, P	86 W
Input reactive power, Q	101 VAR

Calculate the series elements of the motor equivalent circuit [8 Marks]

(Include your calculations for determining the series elements of the motor equivalent circuit.)

assuming that the slip, $\eta = 1.0$, and ignore R_0 and X_0 because it is equivalent to a transformer short circuit test

$3P_\phi$

$$3I^2\left(R_1 + R_2^{'}\right) = 3\times P_{input} 3 * 4.46^2\left(R_1 + R_2^{'}\right) = 3 * (86)$$
$$(R_1 + R_2') = 4.32\,\Omega$$

$Z = (R_1 + R_2') + j(X_1 + X_2')$

$$|Z| = \frac{|V|}{|I|} = \sqrt{\left(R_1 + R_2^{'}\right)^2 + j\left(X_1 + X_2^{'}\right)^2} \frac{29.75}{4.46} = \sqrt{(4.32)^2 + j\left(X_1 + X_2^{'}\right)^2}$$
$$\left(X_1 + X_2^{'}\right) = 5.08\Omega$$

Assuming $X_1 = X_2'$ and $R_1 = R_2'$, we obtain

$$\frac{X_1 + X_2'}{2} = \frac{5.08}{2} = 2.54\,\Omega$$
$$\frac{R_1 + R_2'}{2} = \frac{4.32}{2} = 2.16\,\Omega$$

Therefore, the values are

$$R_1 = R_2' = 2.16\,\Omega$$
$$X_1 = X_2' = 2.54\,\Omega$$

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No-load test results (Small Slip) [4 Marks]

Measurements	Value (Unit)
Stator voltage, V	132.8 V_{RMS}
Stator current, I	2.97 A_{RMS}
Input real power, P	61 W
Input reactive power, Q	392 VAR

Results (Zero Slip) [4 Marks]

Measurements	Value (Unit)
Stator voltage, V	145.2 V_{RMS}
Stator current, I	4.43 A_{RMS}
Input real power, P	98 W
Input reactive power, Q	708 VAR

Calculate the shunt elements of the motor equivalent circuit [8 Marks]

(Include your calculations for determining the shunt elements of the motor equivalent circuit)

<u>*No load test at synchronous speed (zero slip)*</u>
Slip = 0
Neglect I_2 and rotational losses at zero slip

Magnetic loss = $P_{3\phi} - 3I_1^2R_1$
From Question 1, $R1$ = 2.16Ω, $P_{\phi} = 105\ W,\ I_1 = 4.43\ A_{rms},\ X_1 = 2.54\Omega$
Magnetic Losses, P_m = 3-phase power - 3 $*\ I_1^2R_1 = 3(99) - 3(4.43)^2(2.16) = 169.83W$

R_0 can be calculated from the magnetic losses

$$R_0 = \frac{3V_{ph}^2}{Magnetic\ Losses} = \frac{3(145.2)^2}{169.83} = 372.426\Omega \qquad X_0 = \frac{V_{ph}}{I_1} - \frac{X_1}{P_m} = \frac{145.2}{4.43} - \frac{2.54}{169.83} = 32.76\Omega$$

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No load test at synchronous speed (zero slip)

Rotational loss, $P_{rotational} = 3P_{3\phi} - 3 \times I_1^2 R_1 - P_m P_{rotational} + P_m$

$$= 3(61) - 3(2.97)^2(2.16)$$
$$= 125.84W$$

Load test results [8 Marks]

Speed (rpm)	Stator voltage (V)	Stator current (A)	Real powe r (W)	Reactive power (VAR)	Torque (Nm)
1492	133.5	3.03	90	395	0.5
1482	133.3	3.05	256	381	1.6
1473	133.1	3.19	420	379	2.7
1463	133.0	3.36	570	369	3.7
1453	132.8	3.55	704	371	4.6
1443	132.3	3.85	880	374	5.8
1433	132.5	4.14	943	369	6.3
1423	131.9	4.30	1082	379	7.3
1413	132.3	4.47	1181	384	8.0

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Calculate the theoretical slip and motor speed for the measured power, and compare them with the experimental values. [8 Marks]

(Show all working steps and calculations)

Synchronous speed, n_s=1500 rpm = 157.08 rad/s

Experimental results

Measured speed, n (rpm)	Slip, ƞ $= \frac{n_s - n}{n_s}$
1492	0.0050
1482	0.0120
1473	0.0180
1463	0.0246
1453	0.0313
1443	0.0380
1433	0.0447
1423	0.0513
1413	0.0580

Theoretical

3-phase power, $P_{3\phi}$ (W)	Torque, $T_L\ (Nm)$	Motor speed $n = \frac{9.55 P_{3\phi}}{T_L}$	Slip, ƞ $= \frac{n_s - n}{n_s}$
90	0.5	1719	-0.1460
256	1.6	1528	-0.0187
420	2.7	1485.556	0.0096
570	3.7	1471.216	0.0192
704	4.6	1461.565	0.0256
880	5.8	1448.966	0.0340
943	6.3	1429.468	0.0470
1082	7.3	1415.493	0.0563
1181	8.0	1409.819	0.0601

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Comparison between theoretical and experimental slip and motor speed

Experimental		Theoretical	
Motor Speed (RPM)	Slip	Motor Speed (RPM)	Slip
1492	0.0050	1719	-0.1460
1482	0.0120	1528	-0.0187
1473	0.0180	1485.556	0.0096
1463	0.0246	1471.216	0.0192
1453	0.0313	1461.565	0.0256
1443	0.0380	1448.966	0.0340
1433	0.0447	1429.468	0.0470
1423	0.0513	1415.493	0.0563
1413	0.0580	1409.819	0.0601

It can be observed at low motor speeds (1413-1473), the theoretical and measured motor speeds as well as the calculated slip values are in the same range. It can also be observed as the motor speed decreases, the slip increases. We attribute the deviations to friction within the rotor and stator coils that led to joule losses as the theoretical values are calculated based on power measurements.

However, when the experiment reaches the 1482 and 1492 RPM range, the theoretical and experimental values differ significantly. A negative slip indicates the induction motor has operated in the generating region, which is unexpected behavior. This large motor speed derived from the power could be due to the motor drawing high apparent power from the line sources, thus increasing the real power dissipated, however, as the rated speed is below 1500 RPM, the torque measuring unit is unable to reflect said theoretical speed in the measurements.

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Discussion

1. Explain in detail the relationship between torque and slip (%) for an induction motor. [10 Marks]

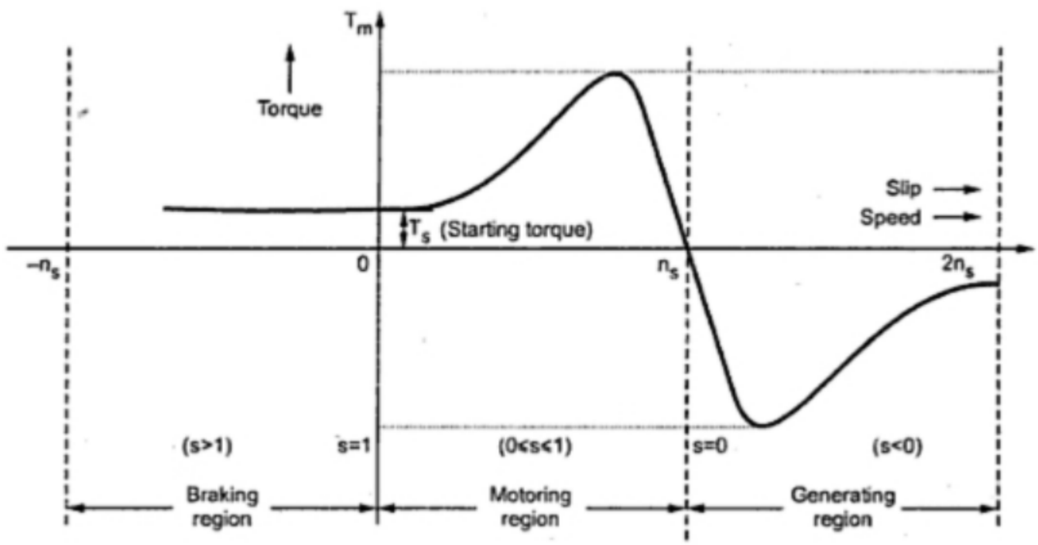

Fig 5: Torque-Slip Curve for 3-phase induction motor [2]

An induction motor is a type of AC motor that works by inducing a rotating magnetic field in the stator (stationary) winding, which then induces currents in the rotor (rotating) winding. These currents in turn produce a magnetic field in the rotor that interacts with the stator field, causing the rotor to turn.

Torque, which is the rotational force generated by the motor, is directly related to the interaction between the magnetic fields of the stator and rotor. The greater the interaction between these fields, the greater the torque produced by the motor.

Slip, on the other hand, is a measure of how much the rotor speed differs from the synchronous speed of the rotating magnetic field in the stator. The synchronous speed is determined by the frequency of the AC power supplied to the motor and the number of poles in the stator winding.

Now, to understand the relationship between torque and slip, it's important to consider the concept of "maximum torque." The maximum torque that an induction motor can produce occurs at a specific value of slip, known as the "pull-out" or "breakdown" slip.

At lower values of slip, the motor is able to produce torque, but the torque is not at its maximum. As slip increases, the motor reaches its maximum torque point, and then as slip continues to increase beyond this point, the torque begins to decrease.

The torque produced by an induction motor is given by the equation:

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$$\tau = k\frac{sV_1^2}{R_2}$$

where T is the torque produced by the motor, k is a constant that depends on the motor design, s is the slip of the motor, R2 is the rotor resistance, and V1 is the applied voltage.

The slip of the motor is given by the equation:

$$s = \frac{N_S - N}{N_S}$$

where Ns is the synchronous speed of the motor and N is the actual speed of the motor.

Thus, we can rewrite the torque equation as:

$$\tau = \frac{k(N_S - N) \times V_1^2}{R_2 \times N_S}$$

From this equation, we can see that the torque produced by the motor is directly proportional to the slip of the motor. In other words, the greater the slip of the motor, the greater the torque produced.

The relationship between torque and slip is not linear. At low slip values, the torque produced by the motor increases as slip increases, but at higher slip values, the torque starts to decrease.

2. Justify the differences between the theoretical (calculated) values and the measured values obtained from this experiment. List at least five methods to prevent any error while obtaining the calculated and measured values. [10 Marks]

Theoretical (calculated) values and measured values in any experiment are inevitably going to differ for a variety of reasons, including measuring instrument limits, environmental circumstances, human error, etc. Analyzing the sources of mistakes that contribute to these differences allows for the justification of the discrepancies between theoretical and measured values.

Instrumental error: The precision of measuring devices used to measure electrical quantities and motor speed, such as voltmeters, ammeters, wattmeters, and torque meters, can have an impact on the accuracy of the measured values.

Human error: Human error can occur during the measurement process due to misreading of values, incorrect data entry, or incorrect calculations.

Ambient conditions: The performance of the motor and, consequently, the measured values, is affected by environmental factors such as temperature, humidity, or the motor condition

Power supply fluctuations: Fluctuations in power supply voltage and frequency can affect the performance of the motor and the accuracy of the measured values.

Mechanical losses: The efficiency of the motor and the precision of the measurement values may both be affected by friction losses

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To prevent errors, some of the methods can be used:

1. Instrument calibration: Doing routine calibration on measuring devices can increase their accuracy and lower instrumental errors.

2. Multiple measurements and take average: Taking multiple measurements then average them help in reducing random errors and improve the accuracy of the measured values.

3. Experiment environment control: Keeping the experimental setup's temperature and humidity constant, and lubricating the motor might decrease the impact of outside factors on the measured data.

4. Use of reliable power supply: Reduce the effect of power supply fluctuations on the motor performance and measured values.

5. Minimizing mechanical losses: Minimizing mechanical losses (friction) in the motor can improve its performance and reduce the effect of mechanical losses on the measured values.

Conclusion and Findings [14 Marks]

In this lab, we have performed a total of 3 main tests which are the locked-rotor test, no load test (small slip and zero slip respectively) and the load test.

Firstly, the locked-rotor test involved locking the rotor and increasing the variac voltage to the point where the rated stator current was achieved. The measured values were then used to calculate the required equivalent circuit parameters.

Secondly, in the no-load test at small slip, the AC input voltage was increased until it reached the rated voltage of 230V. The measured values were used to calculate the remaining equivalent circuit parameters.

Thirdly, in the no-load test at zero slip, the DC supply was turned on and the AC input voltage was adjusted to restore the motor speed to a value close to its synchronous speed of 1500rpm. Some equivalent circuit parameters were measured and the rotational losses were calculated using values obtained from both no-load tests.

Finally, in the load tests, an AC supply of 230V was applied along with the DC supply. The resistive load and shunt regulator were adjusted regularly to decrease the speed by 10rpm to take the required readings. Through these tests, the torque-speed characteristics of the motor were explored from both experimental and theoretical perspectives.

The aims of this experiment are:
(i) To find the equivalent circuit parameters of a three phase, wound rotor AC induction motor.
(ii) To measure the torque-speed characteristics of the motor from standstill to synchronous speed when operated from a 50 Hz supply.

In the experiment, a three-phase, wound rotor AC induction motor was tested to determine its equivalent circuit parameters. The locked-rotor test was conducted to measure the stator voltage, current, input real and reactive power, and using the V/A/W meter, the values of R1, R2', X1, and X2' were calculated using a slip value of 1. Similarly, the no-load test was conducted to measure the set speed, stator voltage, current, input real and reactive power, and using the V/A/W meter, the values of R0, X0, and magnetic losses were calculated using a slip value of 0. Additionally, the rotational loss

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was determined using the measured values from the locked-rotor and no-load tests at small slip. Thus, the first aim of the experiment, which was to find the equivalent circuit parameters of the motor, was achieved.

To complete the experiment, load tests were carried out on the motor. These tests involved taking readings of stator voltage and current, input real and reactive power, speed, and motor torque for decrements of every 10-rpm starting from 1492 rpm. By conducting these tests, the torque-speed characteristic of the motor was determined from synchronous speed to the point where the excitation current reached its rated value, i.e., the full load condition was met. Thus, the second aim of the experiment was also accomplished.

The comparison of the measured values are listed in the table below.

Test	Stator Voltage, V	Stator Current, I	Input Real Power, P	Input Reactive Power, Q
Locked-Rotor Test	29.75 V_{RMS}	4.46 A_{RMS}	86 W	101 VAR
No-Load Test (Small Slip)	132.8 V_{RMS}	2.97 A_{RMS}	61 W	392 VAR
No-Load Test (No Slip)	145.2 V_{RMS}	4.43 A_{RMS}	98 W	708 VAR

As we can see, the experimental results in the table above are very similar to the theoretical value.

In the locked-rotor test, the rotor does not rotate and the speed will become zero. Thus, the full load current passes through the stator current at a high current value of 4.46 $A_{RMS\ which}$ is quite similar to its rated value [1].

During the no-load test with small slip, the rotor requires only a small torque to overcome frictional and iron losses, resulting in a small slip [2]. A small slip indicates that the rotor speed (n) is very close to the speed of the rotating magnetic field (ns).

Conversely, during the no-load test with zero slip, the rotor speed (n) is equal to the rotating magnetic flux speed (ns). Since n was held constant at around 1500 rpm (actual value is 1492 rpm), it is the speed of the rotating magnetic field (ns) that increases during the no-load test with zero slip, leading to an increase in V, I, P, and Q.

Regarding the load test (as observed from the load test results above), all measured values (stator current, real power, and torque) except stator voltage and reactive power increase as the speed decreases. However, the stator voltage and reactive power remain relatively constant as the speed decreases. This might be due to the fact that the resistance of the load stays constant during the load test, resulting in no change in load voltage and no impact on the stator voltage. As the load is resistive, the change in rotor speed should not affect reactive elements in the motor. The series elements and shunt elements of the motor equivalent circuit were also calculated in this experiment.

From the load tests, we also found that torque increases linearly with the decreasing motor speed when the motor speed is operating within the region from synchronous speed to full load condition (where the excitation current reaches its rated value) [3].

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References (Minimum 3 References) [6 Marks]

[1] Electrical4U. "Blocked Rotor Test of Induction Motor". Electrical4U.com. 2023 [Online] Available: https://www.electrical4u.com/blocked-rotor-test-of-induction-motor/ (Accessed: 11 April 2023).

[2] "High slip region", Electricallive.com, 2023. [Online]. Available: https://electricallive.com/2015/03/torque-slip-characteristics-in-three.html (Accessed: 11 April 2023).

[3] T. Wildi, "Three-Phase Induction Machines," in Electrical Machines, Drives, and Power Systems, 6th ed., UK: Pearson, ch. 13, pp. 271-314.

[4] S. M. Corp., "What are Torque Motors and how they work?," What Are Torque Motors and How They Work?-Blog-Sesame Motor Corp. [Online]. Available: https://www.sesamemotor.com/blog_detail/en/what-are-torque-motors#:~:text=Torque%20motor%20is%20a%20special,by%20increasing%20the%20rotor%20resistance. [Accessed: 16-Apr-2023].

[5] "Induction Motor," Induction Motor - an overview | ScienceDirect Topics. [Online]. Available: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/induction-motor#:~:text=and%20Gas%2C%202019-,Induction%20Motors,magnetic%20field%20in%20the%20stator. [Accessed: 16-Apr-2023].

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in text citation for reference 4 and 5 not found (minus 2 marks)

checked

MONASH University
MALAYSIA

SCHOOL OF ENGINEERING

ELECTRICAL AND COMPUTER SYSTEMS ENGINEERING

LABORATORY REPORT MARKING RUBRIC

ECE3051: ELECTRICAL ENERGY SYSTEMS

Experiment Number: 4

Title of Lab Sheet:

Group Number:

No.	Student ID	Name of Group Members	Total Marks
1	30720230	Loh Jia Quan	97/100
2	31106889	Agill Kumar Saravanan	97/100
3	30719305	Huan Meng Hui	97/100
4	32194471	Tan Jin Chun	97/100
5	32259417	Chong Yen juin	97/100

MARKS BREAKDOWN

Section	*Total Score*	*Actual Marks*	*Scoring Band*	*Criteria*	*Comment*
Results	*40*		*30-40*	*Clear and completely labelled figures of the experiment/simulation results with justifications and tables. A detailed caption is provided for each figure with an in-text figure reference. The x-axis and y-axis are labelled with the unit in the bracket. The legend is provided whenever it is deemed to be required. If there is more than one line, the lines should be clearly distinguishable with the visible difference such as dotted line, dashed line and solid line, even in black and white.*	40
			20-30	*Some of the figures of the experiment/simulation setup are not clear, do not have any labelling/ caption/ in-text caption reference/ distinguishable multiple lines and are blurry. The table and justification have mistakes or errors.*	
			0-20	*Insufficient amounts of figures and labelling of the experiment/simulation layout setup, which is not correct and/or unclear. The table is not filled.*	
Discussion	*40*		*30-40*	*Complete data collection and presentation using tables/figures/ graphs with appropriate labels. Discussion of the results with prudent judgment. Have a comparison of the measured results with theoretical values and in-text citations from the peer-reviewed references. The comprehensive comparison, evaluation and justification of the results are given with clear explanation to demonstrate the understanding of the laboratory.*	40
			20-30	*The discussion shows little understanding of what the experiment/simulation is all about. Brief comparison, evaluation and justification of the results, with unclear/ incorrect explanation on the theoretical and experimental/ simulation results.*	
			0-20	*Only restatement of the results without commenting on the expected key points. Incorrect judgment/ arguments were used. No comparison, evaluation and justification of the results, with an unsatisfactory explanation on the theoretical and experimental/ simulation results.*	
Conclusion, References and Appendix	*20*		*15-20*	*Explained how the aims of the experiment have been achieved. The key features of the methods used, the most important results and the findings of the laboratory have been summarized. Complete references list to any book, articles and websites is provided with proper in-text citations in correct formatting. The appendix is provided in detail.*	17

			10-15	*A conclusion is drawn but is not supported by the experimental/ simulation evidence and a clear understanding of the findings. Incomplete references to the books or any other sources used in the report and the in-text citations are inappropriate or incorrect. The appendix is partially provided.*	
			0-10	*No sensible conclusion. The referencing is presented in the wrong format. No evidence, attachments, appendices are attached. Irrelevant referencing was used. Unclear understanding of the experiment without a summarized conclusion and the evidence of results. No appendix is provided.*	
Total	*100*				97

Examiner/ Assessor of ECE3051: Electrical Energy Systems
Date: 5/5/2023

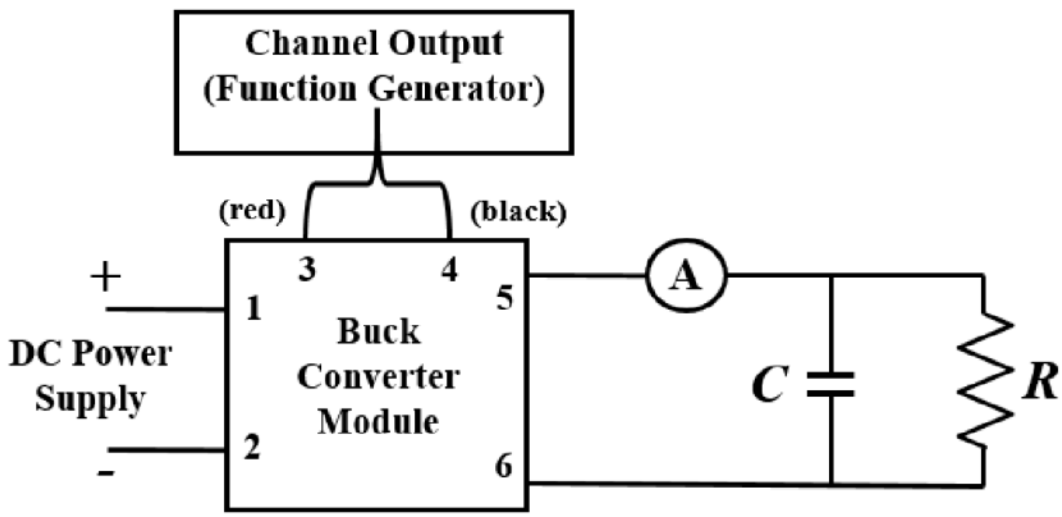
To-Do

Set the resistive load to 20 Ω.

Connect all three phases of the capacitive load in series.

Take the capacitance value for every Knob position using an LCR meter. The power must be off during taking the measurement.

For experimental setup, follow the connection scheme shown in Figure 5.



DC power supply is used for providing input voltage for the buck converter module.

Be careful about DC polarity.

The arbitrary function generator is used to provide PWM switching pulses of required frequency and duty cycle for the buck converter

Turn the DC power supply on and set the DC supply to 15 V.

Next, turn the arbitrary function generator on and select ‘Pulse’ in ‘Continuous ‘ mode with frequency of 1 kHz. Set the duty ratio as 30%, amplitude as 5 V and the offset as 2.5 V.

Repeat the exercise for each of the knob position of the capacitor load. Compare the calculated values with the theoretical values

Take reading of average output voltage and output voltage ripple (How to get ripple from CRO ?) for duty ratio of 50% and 70% for each of the knob position of the capacitor load

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EXPERIMENT 4

DC-DC Buck Converter

1. Experimental Setup [10 Marks]

(Draw the circuit of the buck converter (5 marks) and label the components (5 marks))

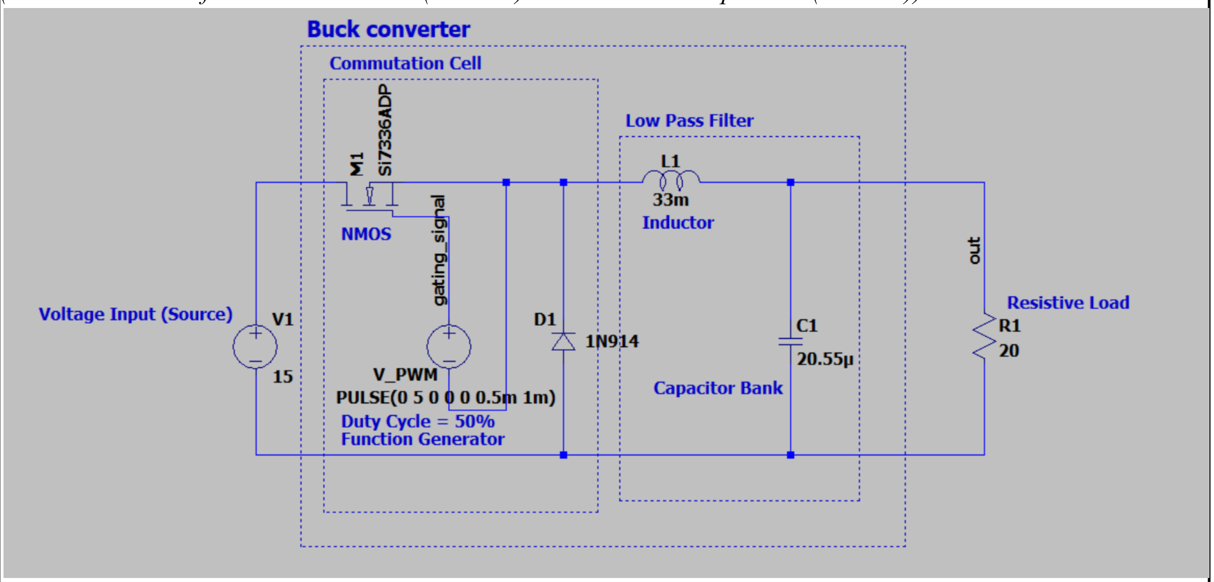


Figure 1. LTSPICE Schematic of Buck Converter

Investigation of voltage ripple

(1) Duty cycle of 30%

Calculate the output voltage ripple for each knob position [2 marks]

(Include your calculations for determining the output voltage ripple for each knob position.)

Output Voltage Ripple

$$\Delta v_0 = \frac{V - V_0}{16LC} DT_s^2$$

Constants
V = 15V
L = 33mH
Ts = 1ms
Fs = 1000Hz
D = 0.3

<u>Knob 1</u>
C =3.348uF
V0 = 3.1V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.3)(1m)^2 \;=\; 2.0195\,V$$

checked

Knob 2
C = 6.734uF
V0 =3.37 V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.3)(1m)^2 = 0.9812\,V$$

Knob 3
C = 10.068uF
V0 = 3.71V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.3)(1m)^2 = 0.6371\,V$$

Knob 4
C = 13.408uF
V0 = 4.04V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.3)(1m)^2 = 0.4644\,V$$

Knob 5
C = 16.755uF
V0 =4.03 V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.3)(1m)^2 \Delta v_0 = 0.3720\,V$$

Knob 6
C = 20.11uF
V0 =4.03 V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.3)(1m)^2 = 0.3099\,V$$

Theoretical Output Voltage

$$V_0 = DV = 0.3(15) = 4.5V$$

Table Results [3 marks]

Table I. Voltage Ripple and Capacitance Value with Duty Cycle = 30%

Knob position	*Capacitance value (F)*	*Average output voltage (V) (from multimeter)*	*Theoretical average output voltage (V) (calculation)*	*Output voltage ripple (V) (from oscilloscope)*		*Theoretical output voltage ripple (V) (calculation)*	*Simulation output voltage ripple (V)*
				Voltage ripple	*Peak-to-peak voltage*		
1	*3.348u*	*3.1*	*4.5*		*15.6*	*2.0195*	*0.8525*
2	*6.734u*	*3.37*	*4.5*		*13.2*	*0.9812*	*0.6825*
3	*10.068u*	*3.71*	*4.5*		*11.8*	*0.6371*	*0.5375*
4	*13.408u*	*4.04*	*4.5*		*10.2*	*0.4644*	*0.4250*
5	*16.755u*	*4.03*	*4.5*		*9.6*	*0.3720*	*0.3500*
6	*20.11u*	*4.03*	*4.5*		*7.8*	*0.3099*	*0.3000*

Show the output voltage ripple waveform (using CRO) for each knob position [3 marks]

(minus 1 mark)

checked

(Insert a picture of your output voltage ripple waveform (using CRO) for each knob position)

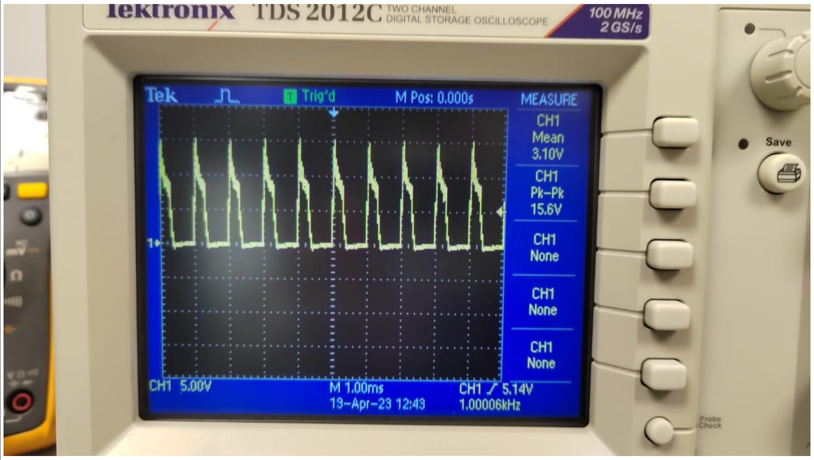


Figure 2 Output voltage waveform for C = 3.348uF and D = 0.3; y-axis is voltage (V) and x-axis is time (ms)

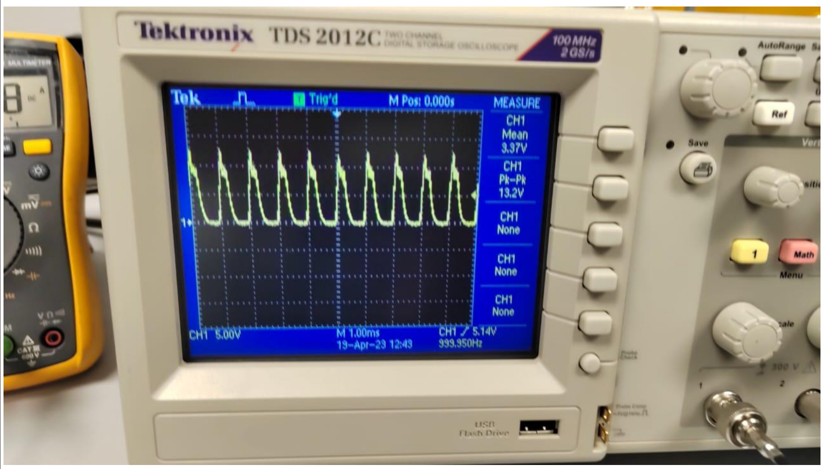


Figure 3 Output voltage waveform for C = 6.734uF and D = 0.3.; y-axis is voltage (V) and x-axis is time (ms)

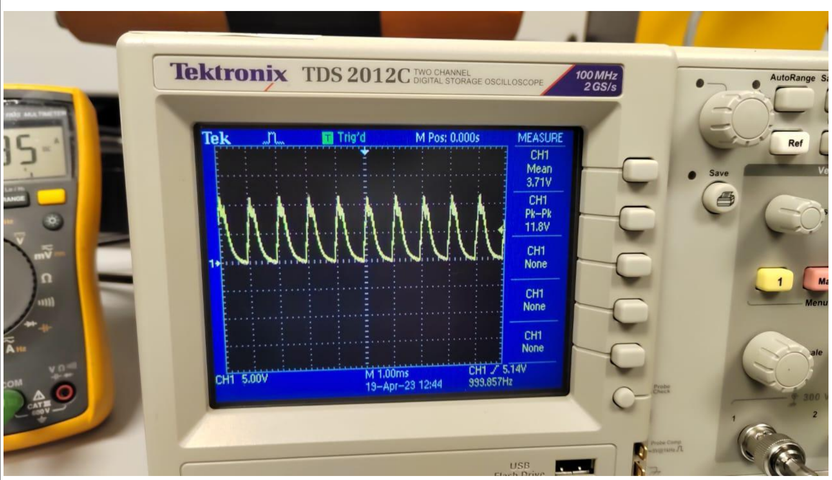


Figure 4 Output voltage waveform for C =10.068μF and D = 0.3.; y-axis is voltage (V) and x-axis is time (ms)

checked

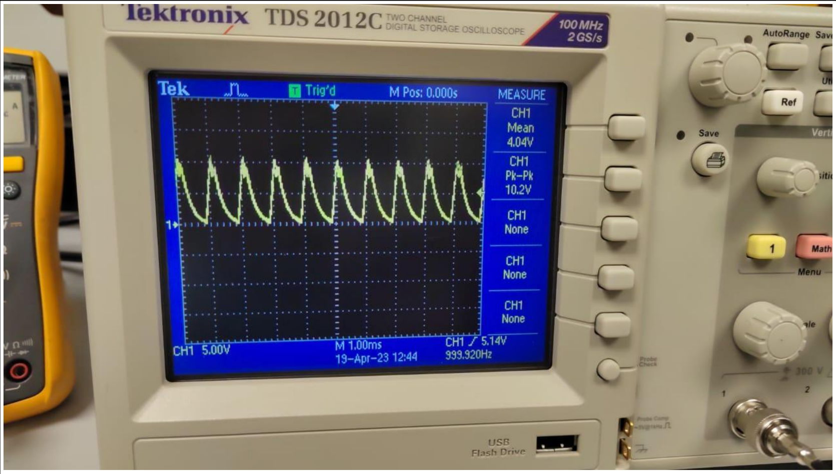


Figure 5 Output voltage waveform for C = 13.408*μF and D = 0.3.; y-axis is voltage (V) and x-axis is time (ms)*

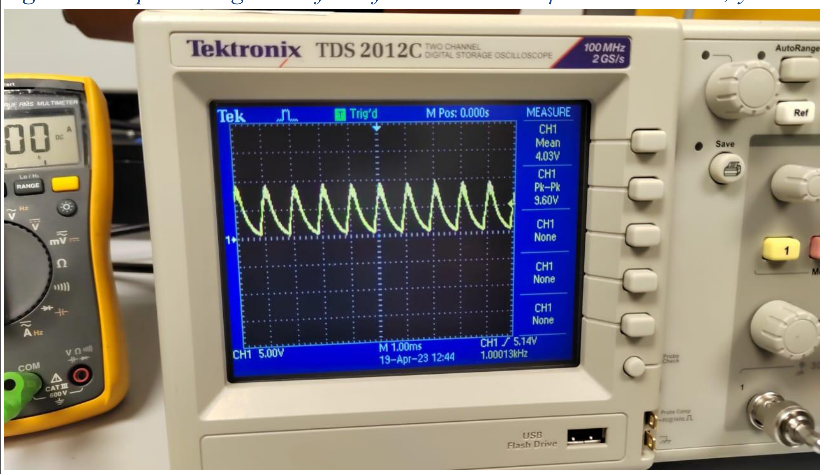


Figure 6 Output voltage waveform for C = 16.755*μF and D = 0.3.; y-axis is voltage (V) and x-axis is time (ms)*

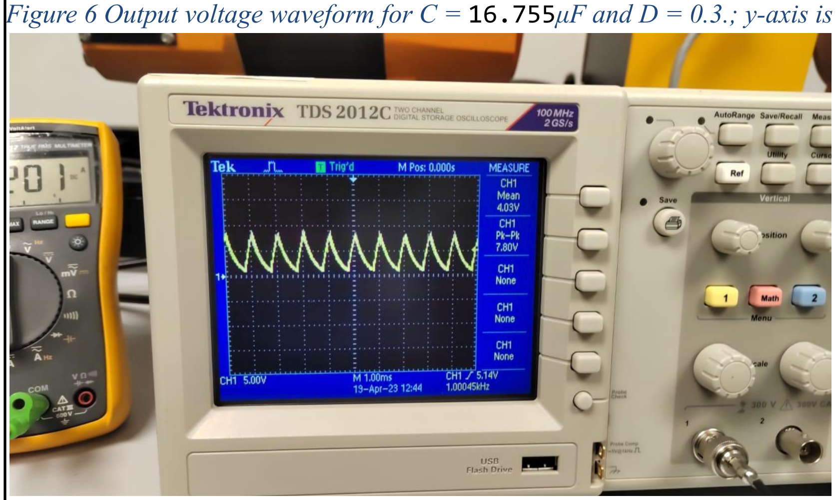


Figure 7 Output voltage waveform for C = 20.11*μF and D = 0.3.; y-axis is voltage (V) and x-axis is time (ms)*

Show the output voltage ripple waveform (from simulation) for each knob position [2 marks]

(Insert a picture of your output voltage ripple waveform (from simulation) for each knob position)

checked

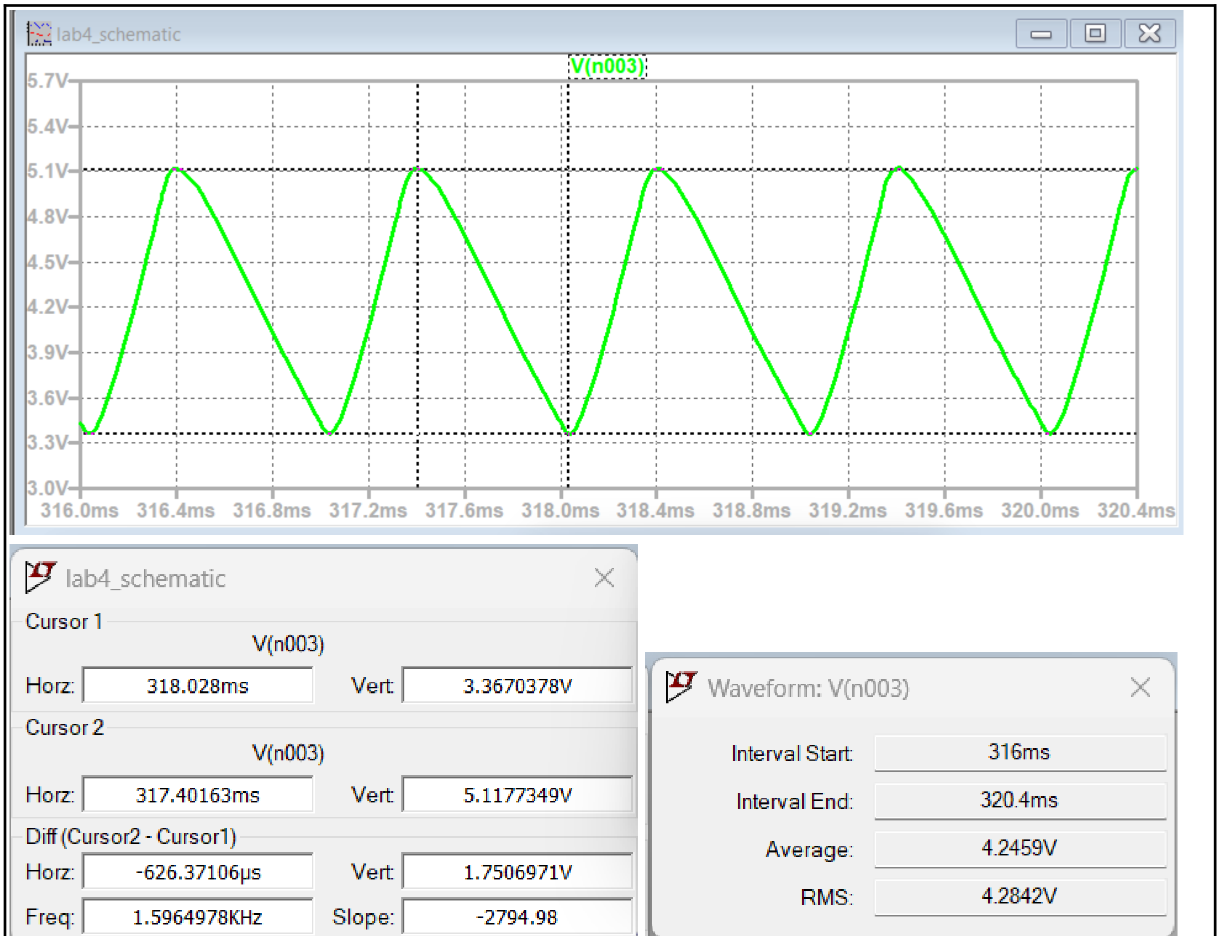
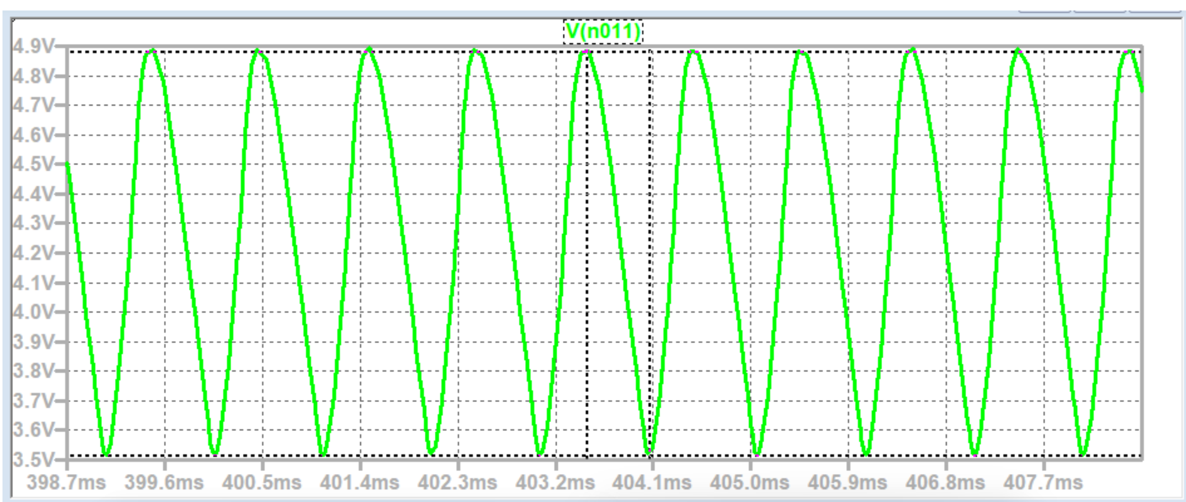


Figure 8 Output voltage waveform for C = 3.348 µF and D = 0.3.; y-axis is voltage (V) and x-axis is time (ms)



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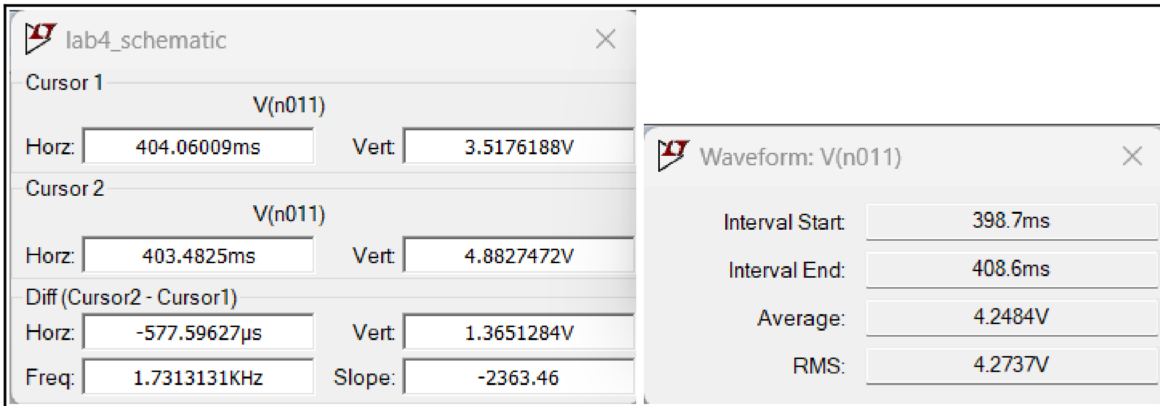


Figure 9 Output voltage waveform for C = 6.734 µF and D = 0.3.; y-axis is voltage (V) and x-axis is time (ms)

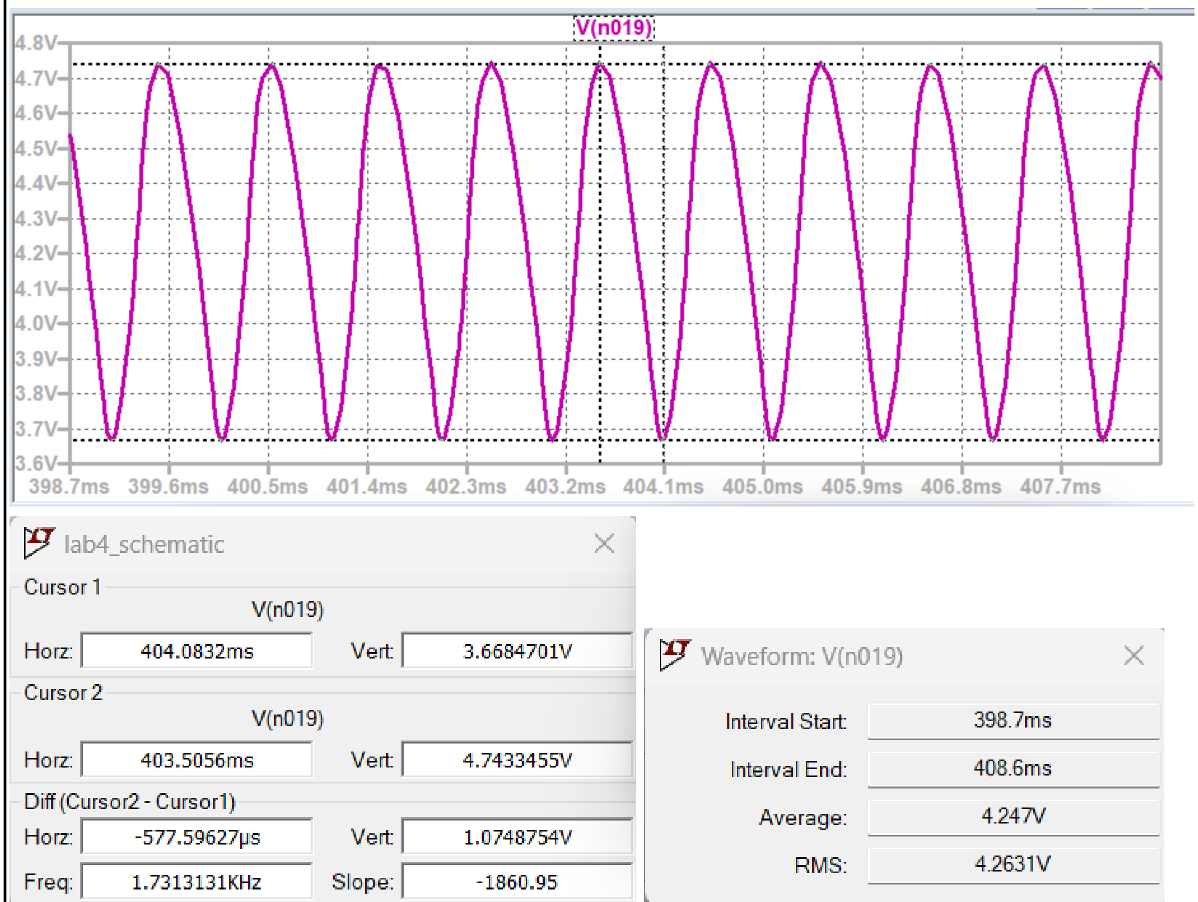


Figure 10 Output voltage waveform for C = 10.068 µF and D = 0.3.; y-axis is voltage (V) and x-axis is time (ms)

checked

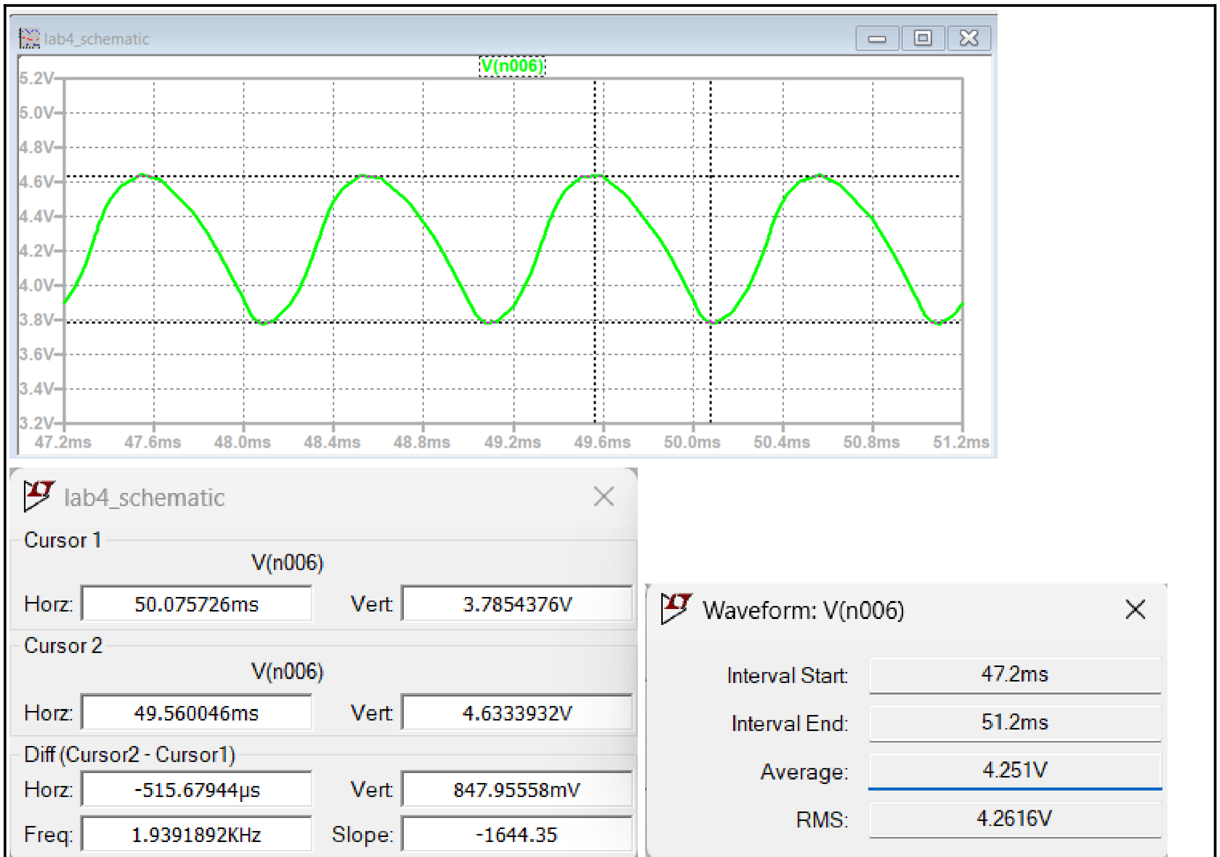
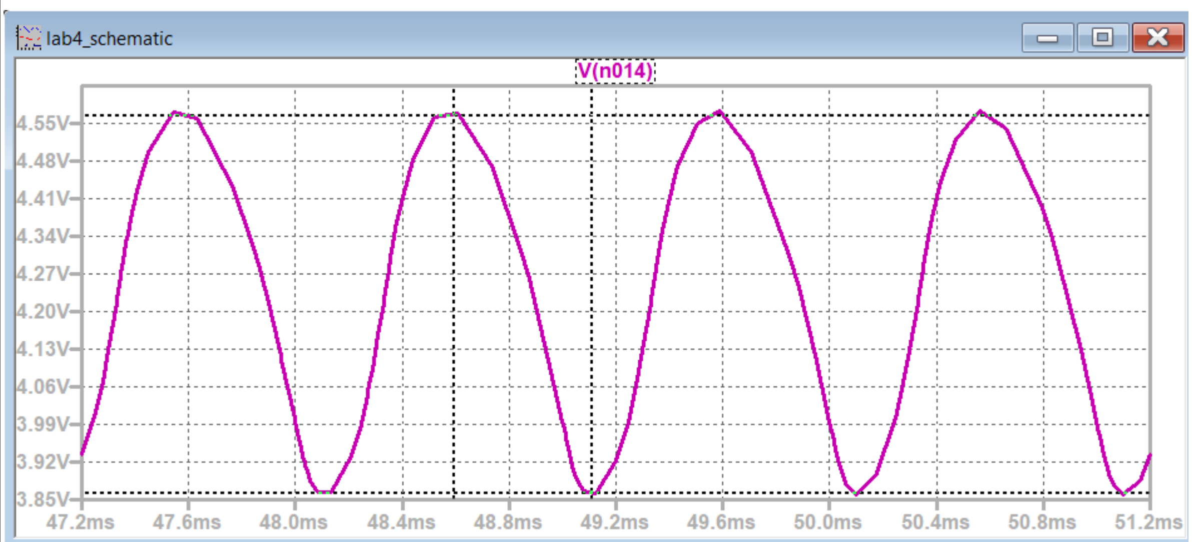


Figure 11 Output voltage waveform for C = 13.408 µF and D = 0.3.; y-axis is voltage (V) and x-axis is time (ms)



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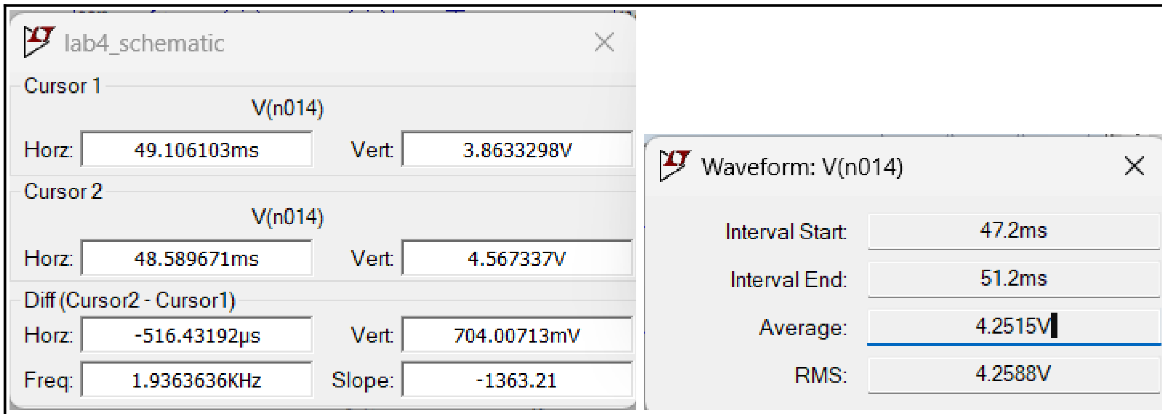
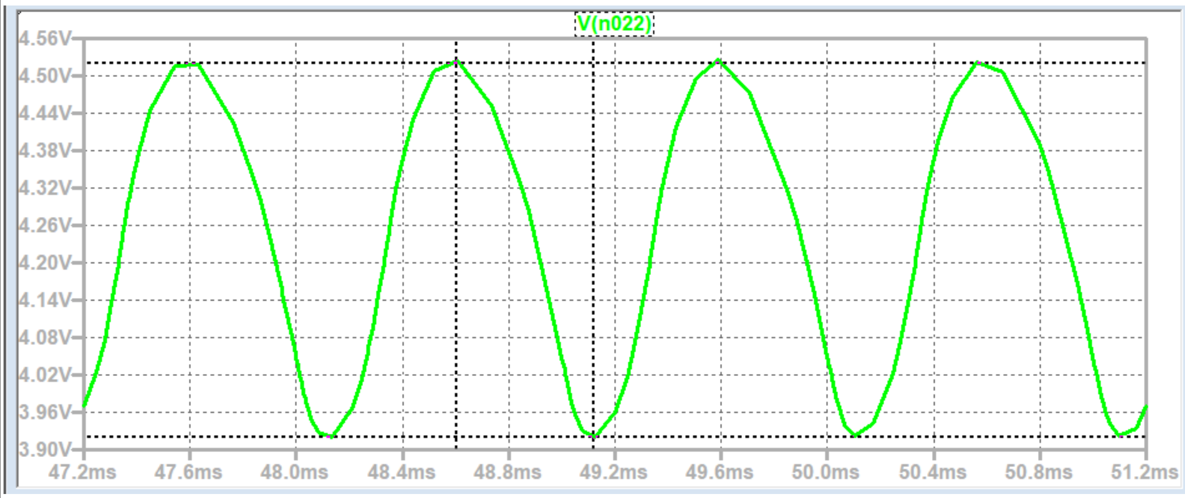


Figure 12 Output voltage waveform for C = 16.755µF and D = 0.3.; y-axis is voltage (V) and x-axis is time (ms)



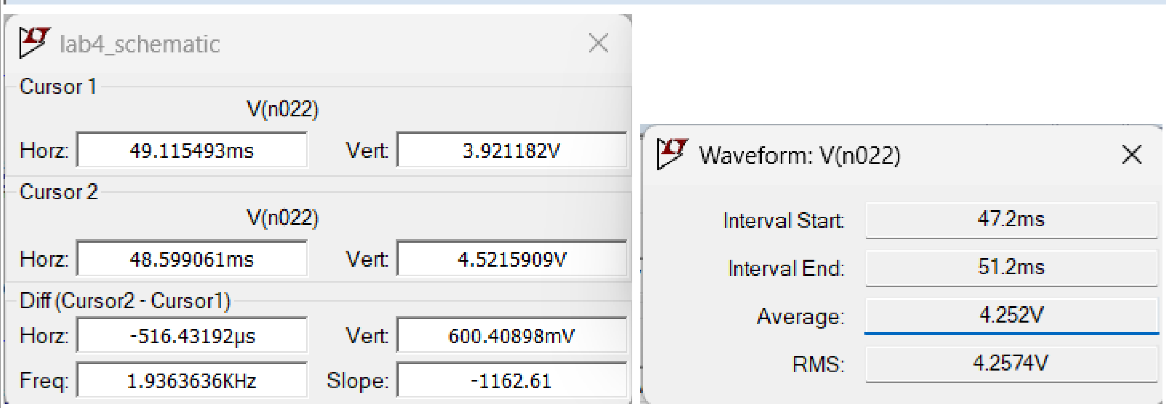


Figure 13 Output voltage waveform for C = 20.1 µF and D = 0.3.; y-axis is voltage (V) and x-axis is time (ms)

(2) Duty cycle of 50%

Calculate the output voltage ripple for each knob position [2 marks]

(Include your calculations for determining the output voltage ripple for each knob position.)

Output Voltage Ripple

$$\Delta v_0 = \frac{V - V_0}{16LC} D T_s^2$$

Constants
V = 15V
L = 33mH
Ts = 1ms

checked

Fs = 1000Hz
D = 0.5

<u>Knob 1</u>
C =3.348u F
V0 = 5.36V

$$\Delta v_0 = \frac{V-V_0}{16(33m)C}(0.5)(1m)^2 = 2.7549V$$

<u>Knob 2</u>
C =6.734u F
V0 =5.57 V

$$\Delta v_0 = \frac{V-V_0}{16(33m)C}(0.5)(1m)^2 = 1.326V$$

<u>Knob 3</u>
C =10.068u F
V0 = 5.94V

$$\Delta v_0 = \frac{V-V_0}{16(33m)C}(0.5)(1m)^2 = 0.8521V$$

<u>Knob 4</u>
C = 13.408uF
V0 = 6.23V

$$\Delta v_0 = \frac{V-V_0}{16(33m)C}(0.5)(1m)^2 = 0.6194V$$

<u>Knob 5</u>
C =16.755u F
V0 =6.49 V

$$\Delta v_0 = \frac{V-V_0}{16(33m)C}(0.5)(1m)^2 = 0.481V$$

<u>Knob 6</u>
C =20.11u F
V0 = 6.68V

$$\Delta v_0 = \frac{V-V_0}{16(33m)C}(0.5)(1m)^2 = 0.3918V$$

Theoretical Output Voltage

$$V_0 = DV = 0.5(15) = 7.5V$$

Table Results [3 Marks]

Table II. Voltage Ripple and Capacitance Value with Duty Cycle = 50%

Knob position	*Capacitance value (F)*	*Average output voltage (V) (from multimeter)*	*Theoretical average output voltage (V) (calculation)*	*Output voltage ripple (V) (from oscilloscope)*		*Theoretical output voltage ripple (V) (calculation)*	*Simulation output voltage ripple (V) (calculation)*
				Voltage ripple	*Peak-to-peak voltage*		
1	*3.348u*	*5.26*	*7.5*		*16.8*	*2.7549*	*1.0170*
2	*6.734u*	*5.57*	*7.5*	?	*14.0*	*1.326*	*0.7920*
3	*10.068u*	*5.94*	*7.5*		*12.8*	*0.8521*	*0.6115*
4	*13.408u*	*6.23*	*7.5*		*10.8*	*0.6194*	*0.4890*
5	*16.755u*	*6.49*	*7.5*		*9.4*	*0.4809*	*0.3960*
6	*20.11u*	*6.68*	*7.5*		*8.8*	*0.3917*	*0.3310*

Show the output voltage ripple waveform (using CRO) for each knob position [3 marks]

checked

(Insert a picture of your output voltage ripple waveform (using CRO) for each knob position)

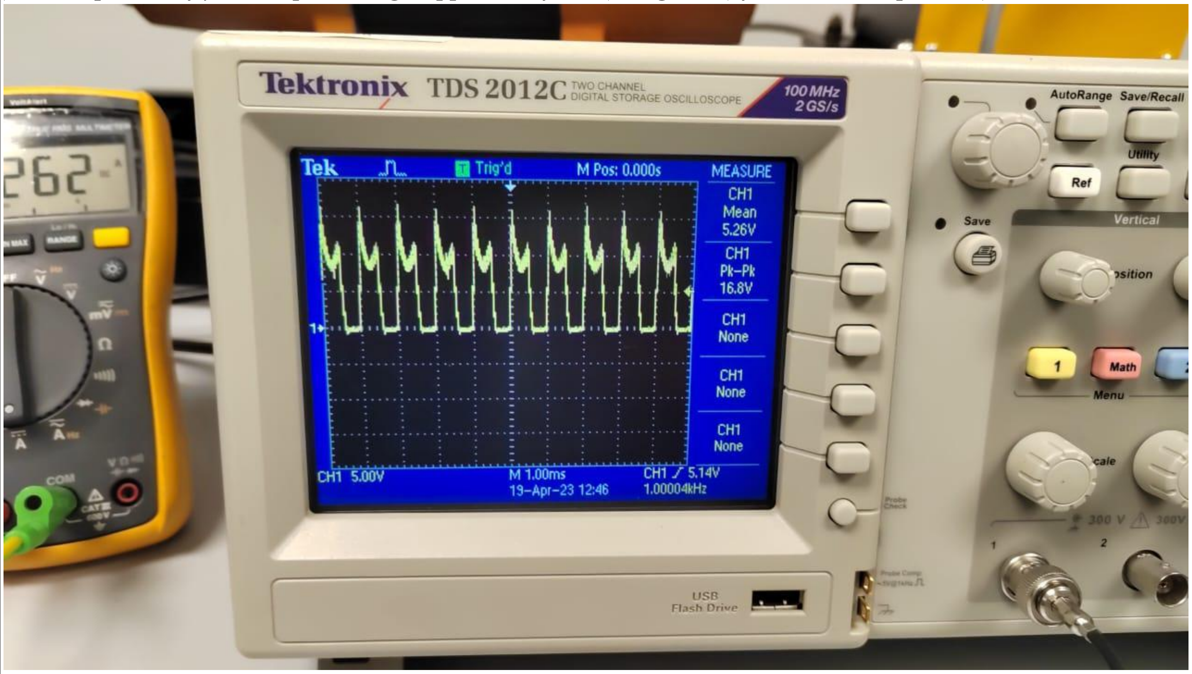


Figure 14 Output voltage waveform for C = 3.348µF and D = 0.5.; y-axis is voltage (V) and x-axis is time (ms)

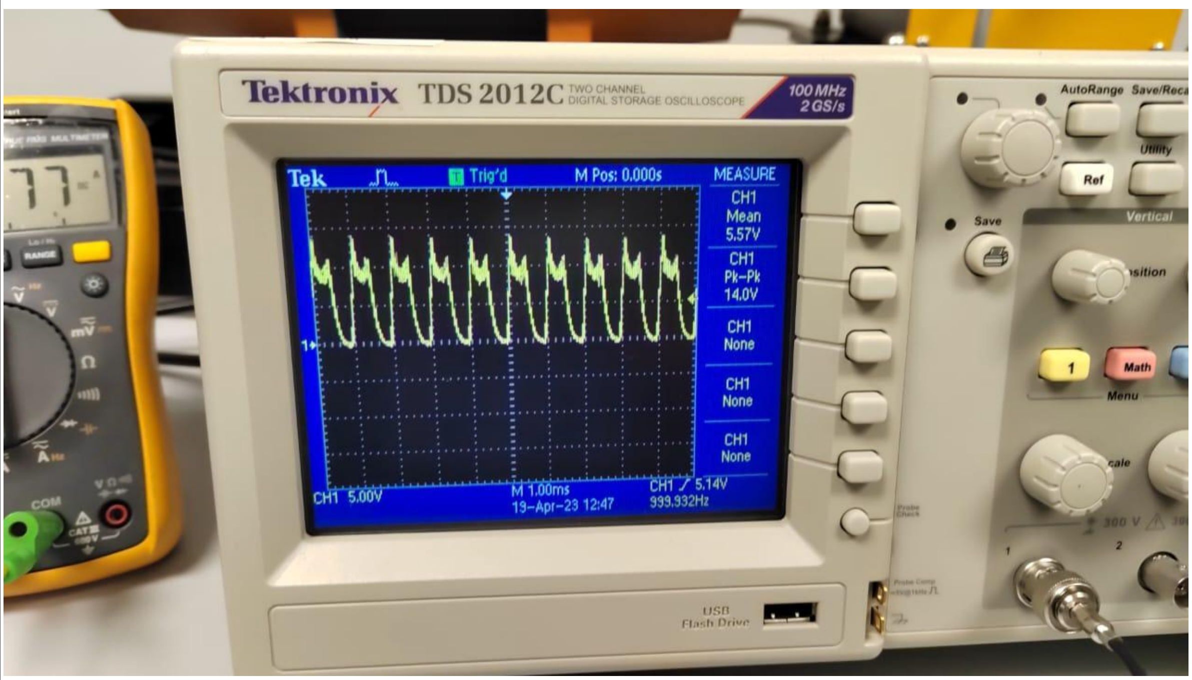


Figure 15 Output voltage waveform for C = 6.734µF and D = 0.53.; y-axis is voltage (V) and x-axis is time (ms)

checked

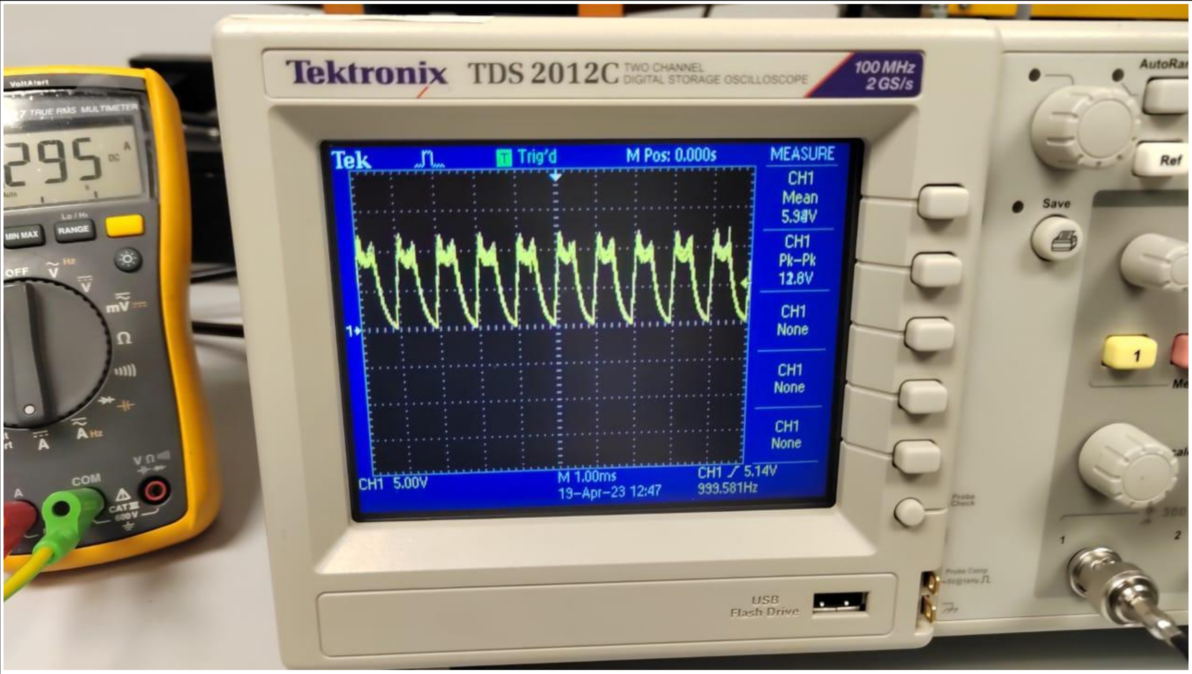


Figure 16 Output voltage waveform for C = 10.068µF and D = 0.5.; y-axis is voltage (V) and x-axis is time (ms)

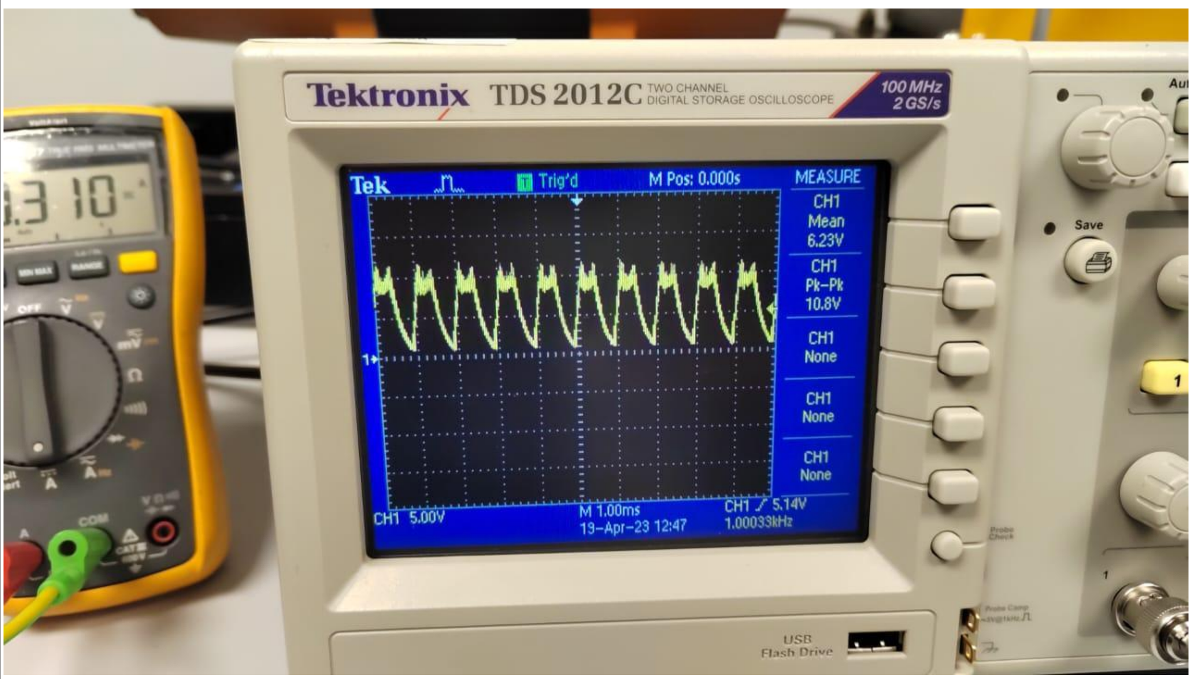


Figure 17 Output voltage waveform for C = 13.408µF and D = 0.5; y-axis is voltage (V) and x-axis is time (ms)

checked

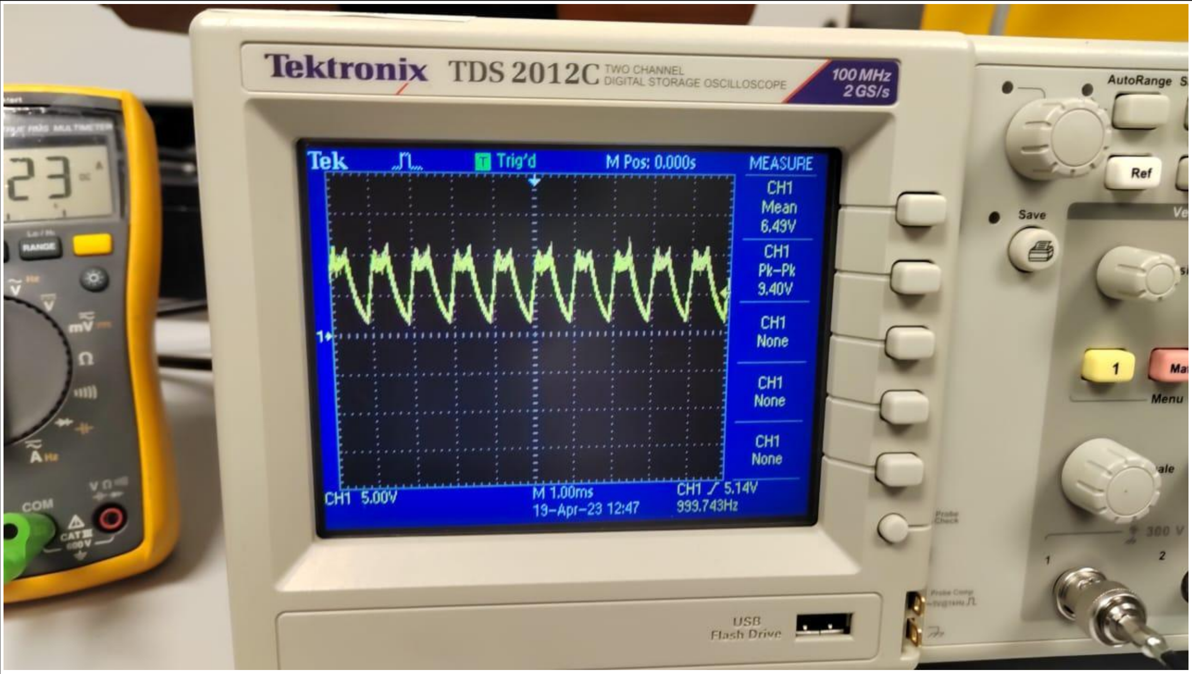


Figure 18 Output voltage waveform for C = 16.755*μF and D = 0.5; y-axis is voltage (V) and x-axis is time (ms)*

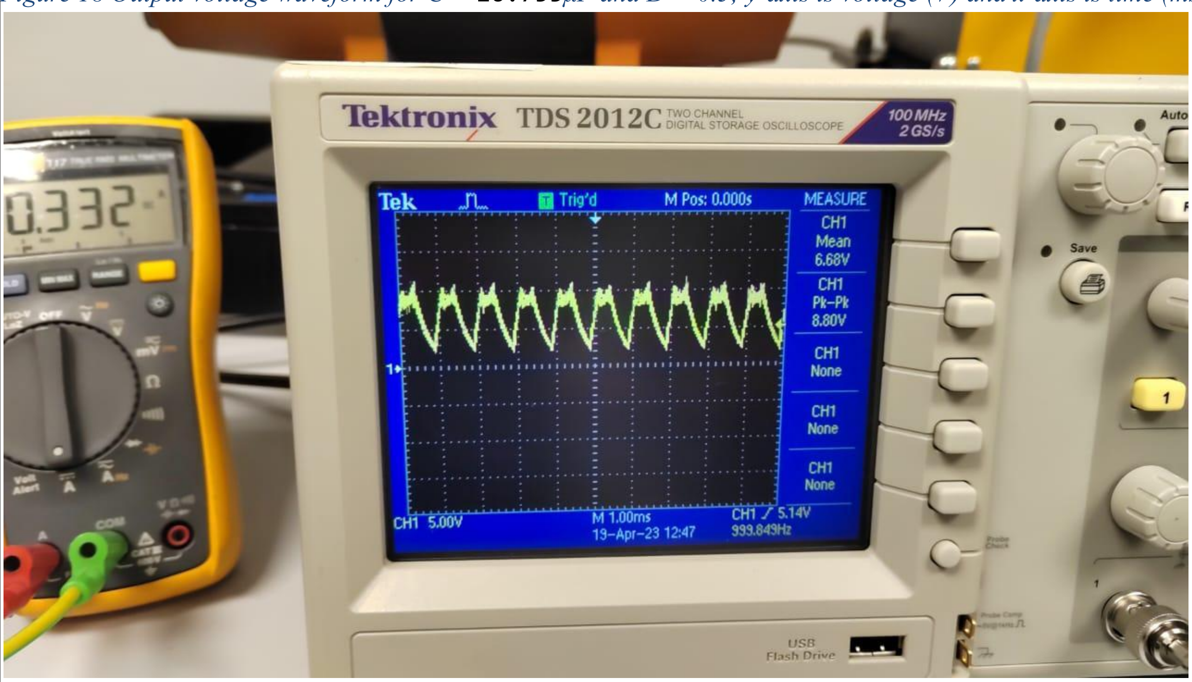


Figure 19 Output voltage waveform for C = 20.11*μF and D = 0.5; y-axis is voltage (V) and x-axis is time (ms)*

Show the output voltage ripple waveform (from simulation) for each knob position [2 marks]

(Insert a picture of your output voltage ripple waveform (from simulation) for each knob position)

checked

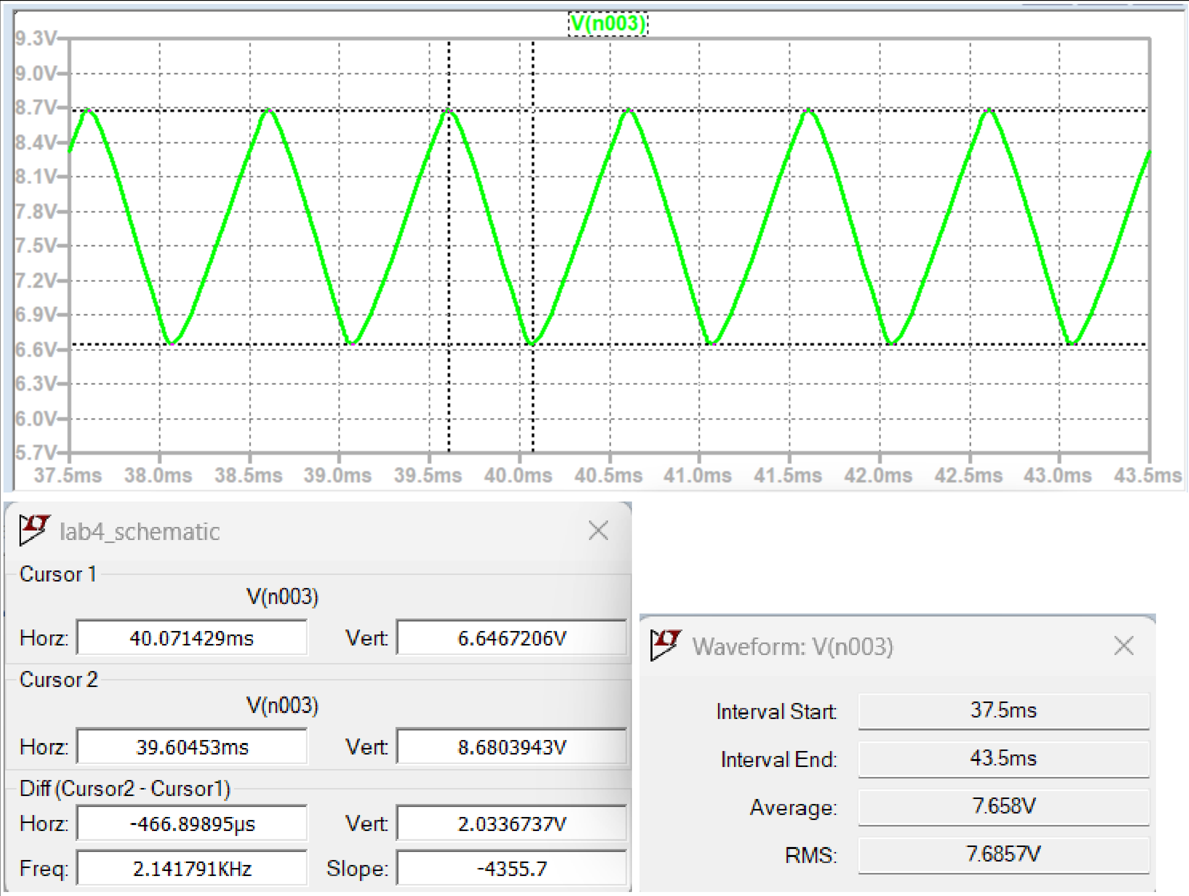
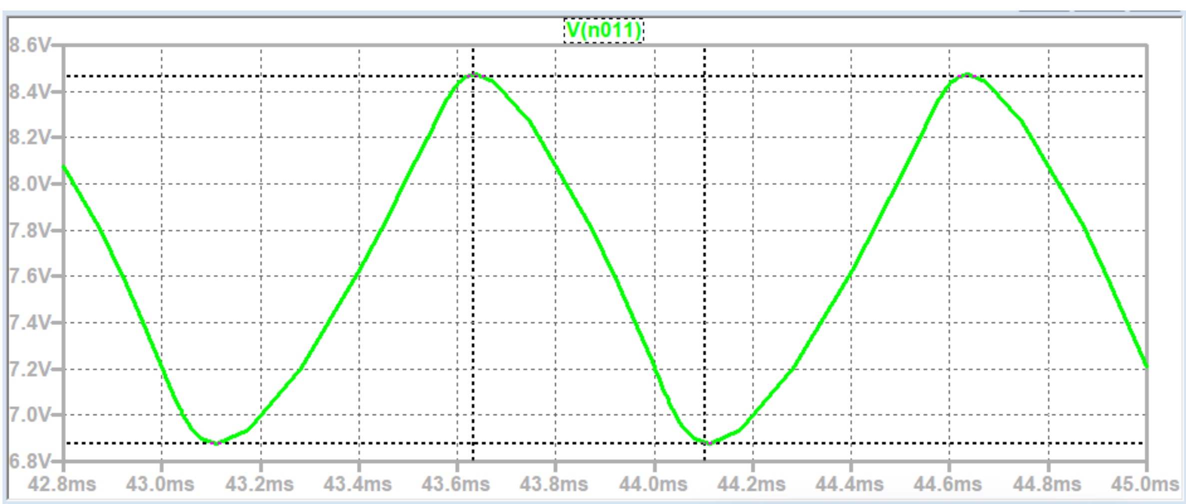


Figure 20 Output voltage waveform for C =3.348 µF and D = 0.5; y-axis is voltage (V) and x-axis is time (ms)



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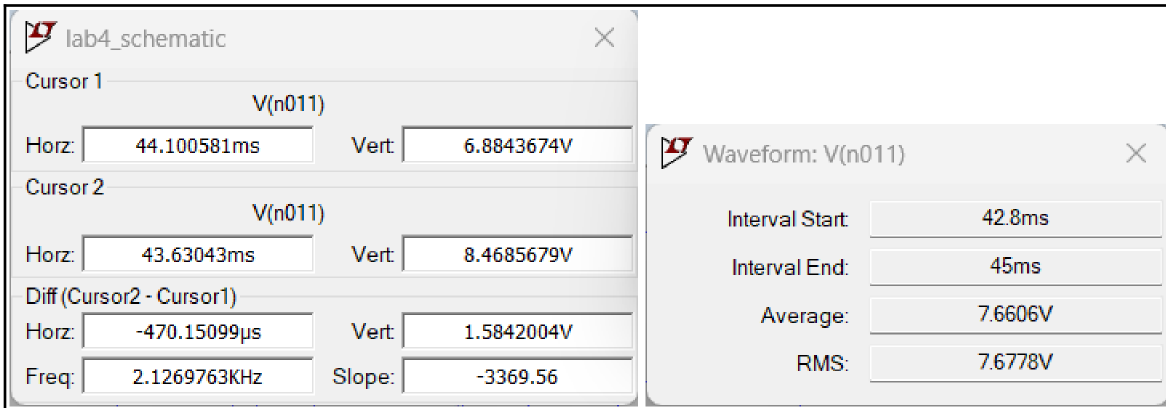


Figure 21 Output voltage waveform for C =6.734 µF and D = 0.5; y-axis is voltage (V) and x-axis is time (ms)

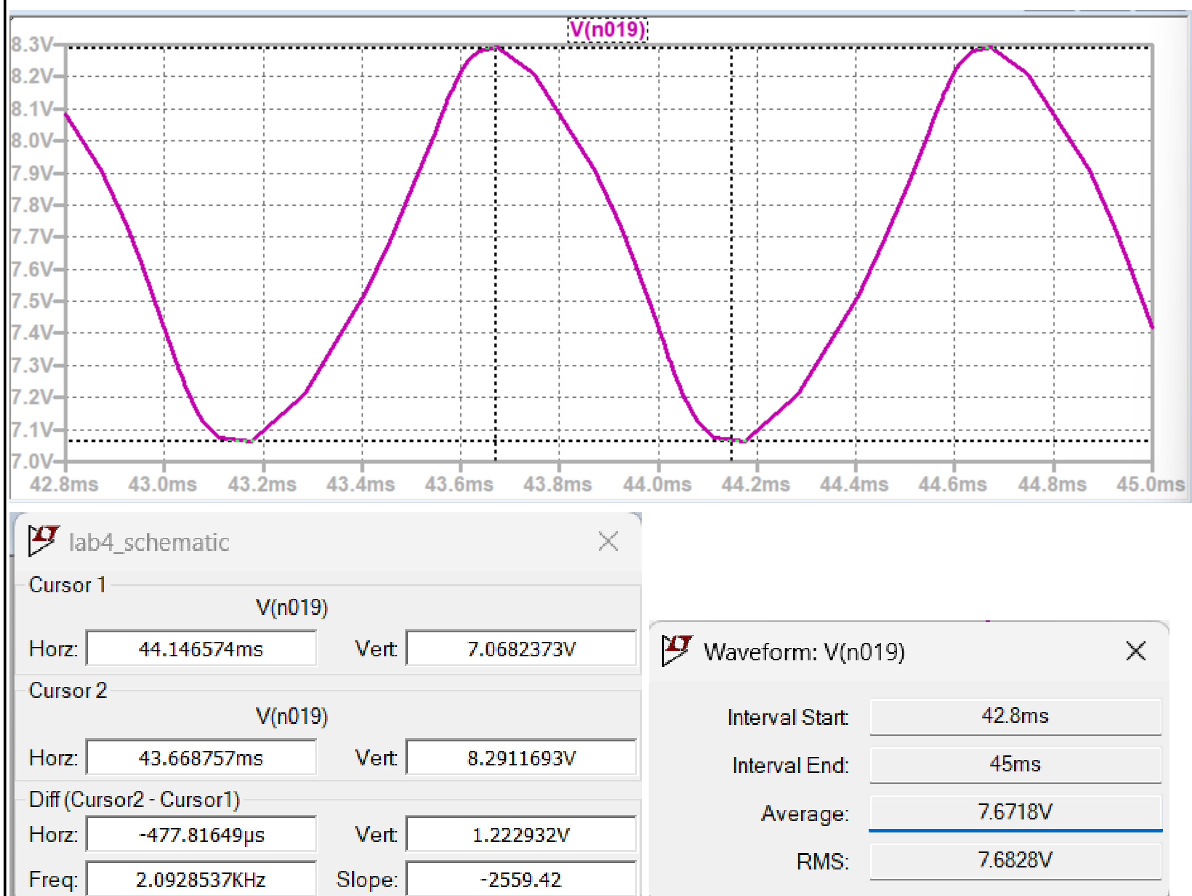


Figure 22 Output voltage waveform for C = 10.068µF and D = 0.5; y-axis is voltage (V) and x-axis is time (ms)

checked

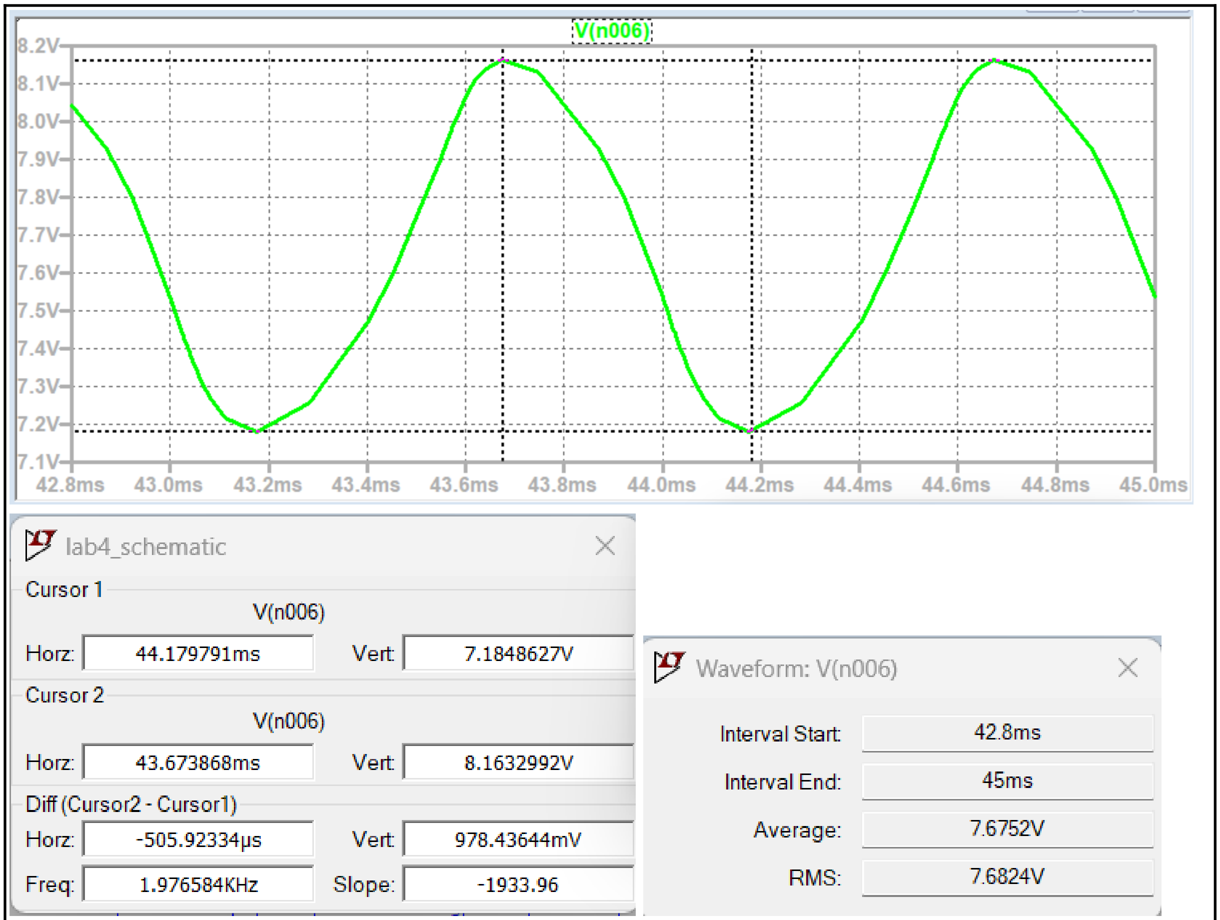
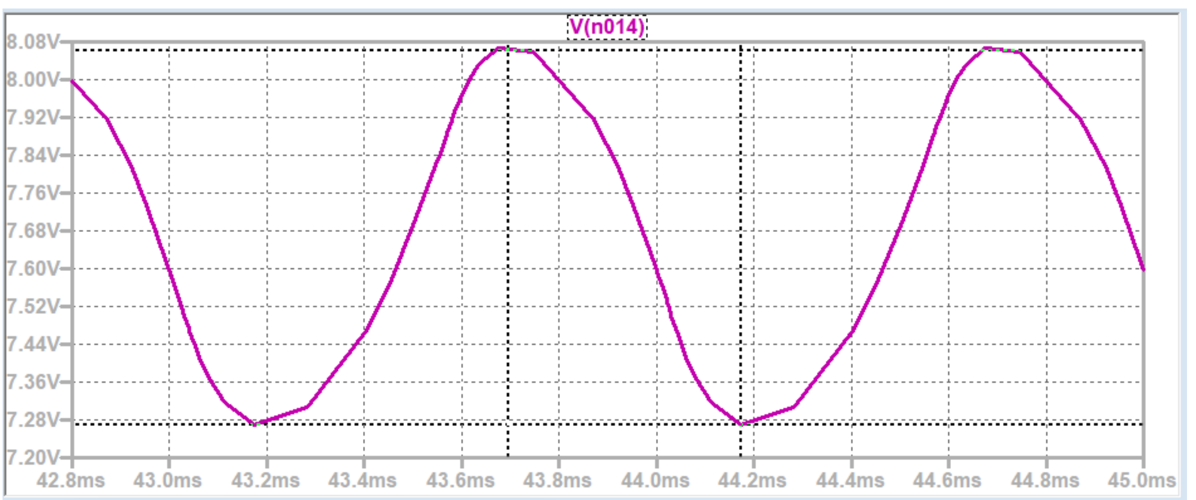


Figure 23 Output voltage waveform for C = 13.408µF and D = 0.5; y-axis is voltage (V) and x-axis is time (ms)



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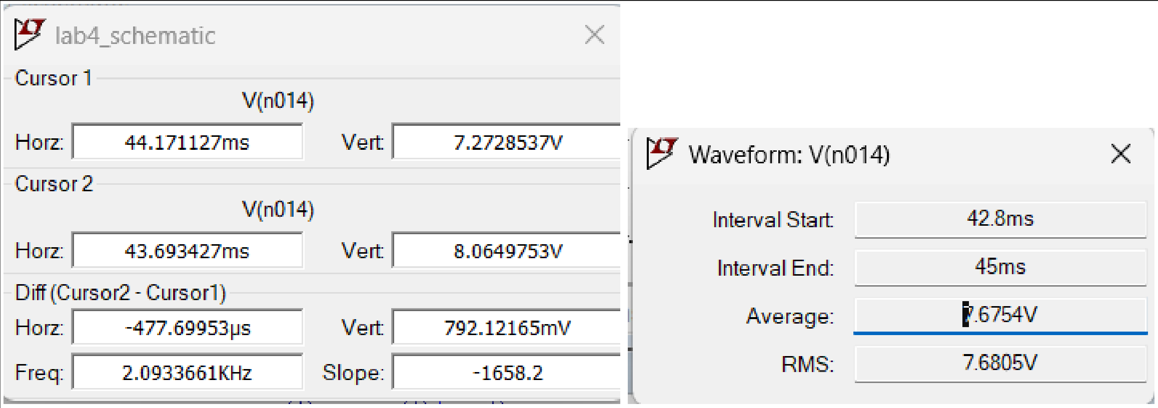


Figure 24 Output voltage waveform for C =16.755 µF and D = 0.5; y-axis is voltage (V) and x-axis is time (ms)

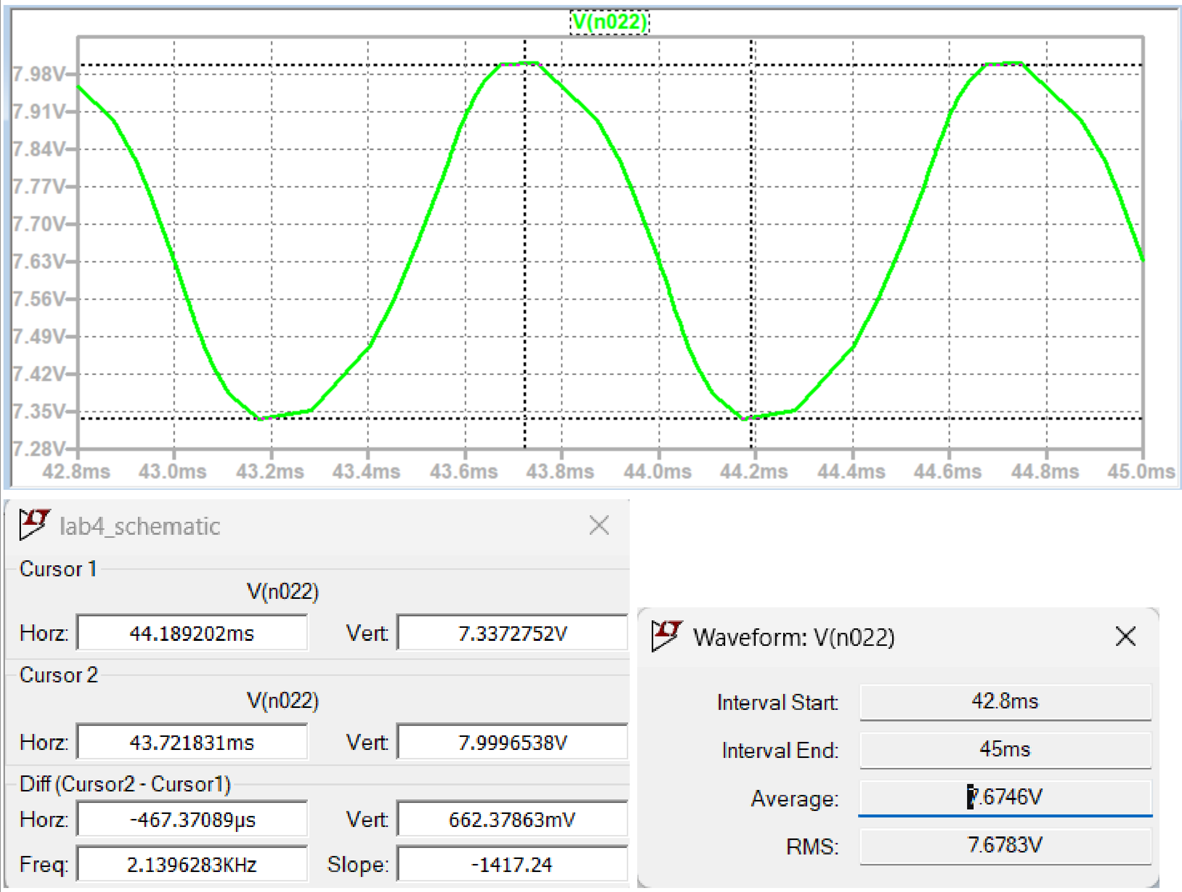


Figure 25 Output voltage waveform for C = 20.11µF and D = 0.5; y-axis is voltage (V) and x-axis is time (ms)

(3) Duty cycle of 70%

Calculate the output voltage ripple for each knob position [2 marks]

checked

(Include your calculations for determining the output voltage ripple for each knob position.)

Output Voltage Ripple

$$\Delta v_0 = \frac{V - V_0}{16LC} D T_s^2$$

Constants

V = 15V

L = 33mH

Ts = 1ms

Fs = 1000Hz

D = 0.5

Knob 1

C = 3.348u*F*

V0 =8.16 V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.7)(1m)^2 = 2.7085V$$

Knob 2

C =6.734u F

V0 = 8.52V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.7)(1m)^2 = 1.2757V$$

Knob 3

C =10.068uF

V0 =8.88 V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.7)(1m)^2 = 0.8058V$$

Knob 4

C = 13.408 uF

V0 = 9.15V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.7)(1m)^2 = 0.5784V$$

Knob 5

C = 16.755 uF

V0 = 9.32V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.7)(1m)^2 = 0.4494V$$

Knob 6

C =20.11 u F

V0 = 9.58V

$$\Delta v_0 = \frac{V - V_0}{16(33m)C}(0.7)(1m)^2 = 0.3573V$$

Theoretical Output Voltage

$$V_0 = DV = 0.7(15) = 10.5V$$

Table Results [3 marks]

Table III. Voltage Ripple and Capacitance Value with Duty Cycle = 70%

Knob position	*Capacitance value (F)*	*Average output voltage (V) (from multimeter)*	*Theoretical average output voltage (V) (calculation)*	*Output voltage ripple (V) (from oscilloscope)*		*Theoretical output voltage ripple (V) (calculation)*	*Simulation output voltage ripple (V) (calculation)*
				Voltage ripple	*Peak-to-peak voltage*		
1	*3.348u*	*8.16*	*10.5*		*17.4*	*2.7085*	*0.7974*

checked

2	6.734u	8.52	10.5		14.0	1.2757	0.6226
3	10.068u	8.88	10.5		12.6	0.8058	0.4760
4	13.408u	9.15	10.5		11.2	0.5784	0.3840
5	16.755u	9.32	10.5		9.6	0.4494	0.3220
6	20.11u	9.58	10.5		8.6	0.3573	0.2715

Show the output voltage ripple waveform (using CRO) for each knob position [3 marks]

(Insert a picture of your output voltage ripple waveform (using CRO) for each knob position)

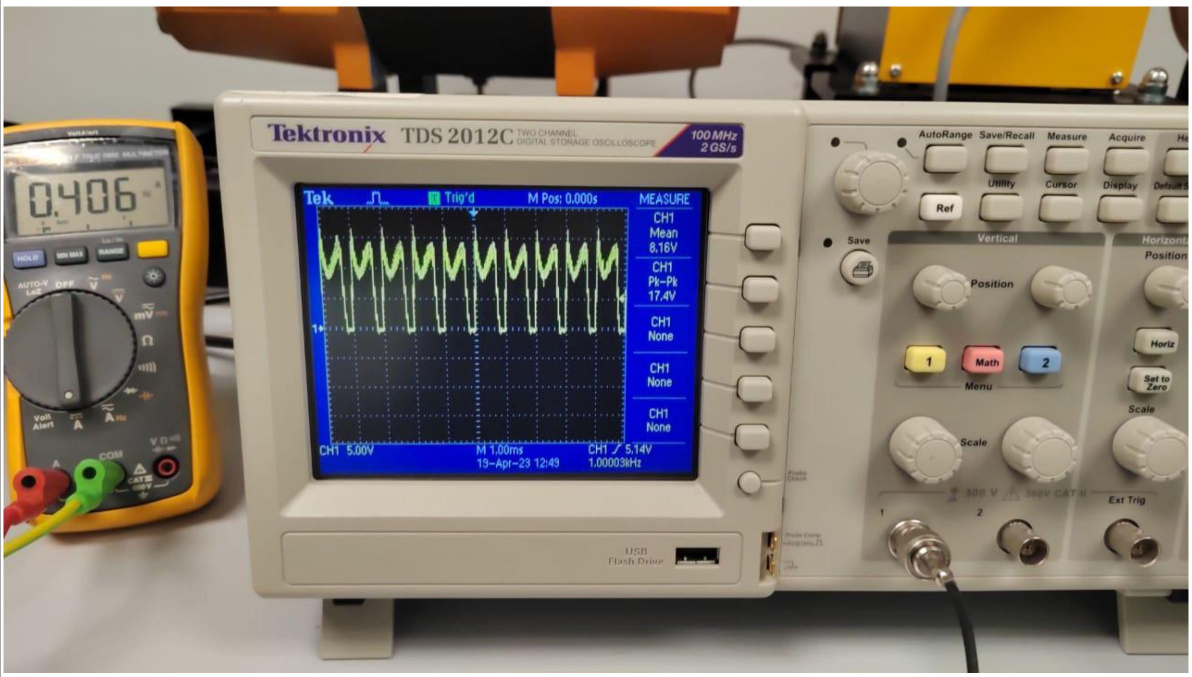
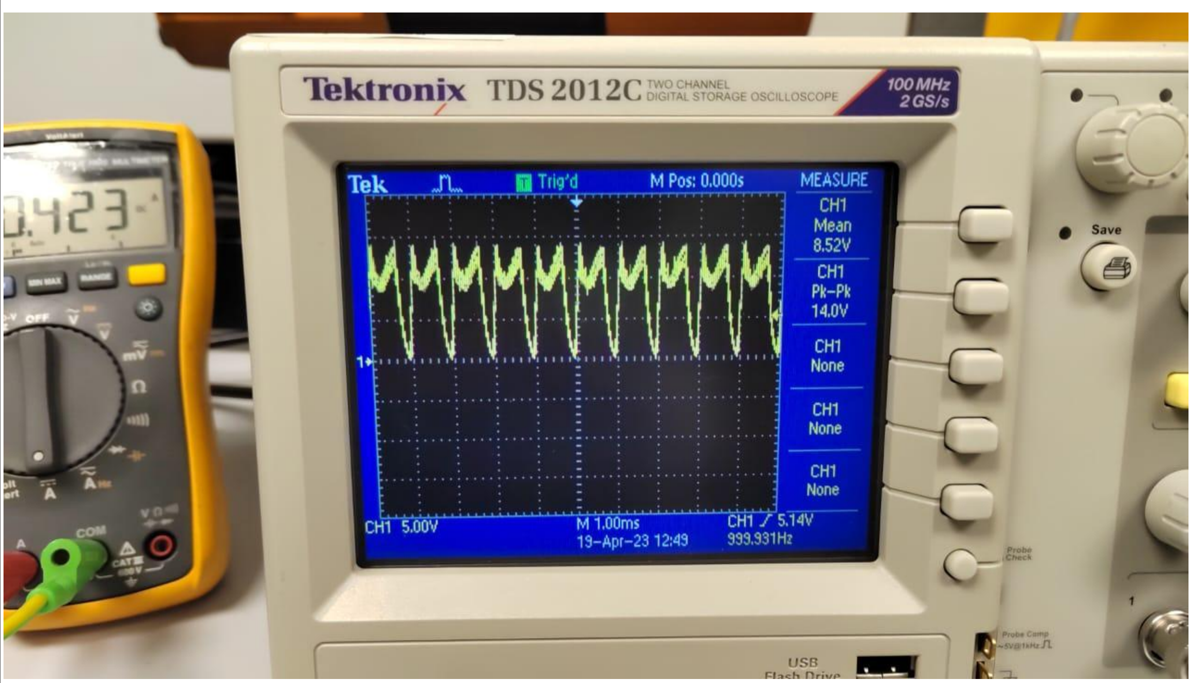


Figure 26 Output voltage waveform for C = 3.348μF and D = 0.7; y-axis is voltage (V) and x-axis is time (ms)



checked

Figure 27 Output voltage waveform for C = 6.734μF and D = 0.7; y-axis is voltage (V) and x-axis is time (ms)

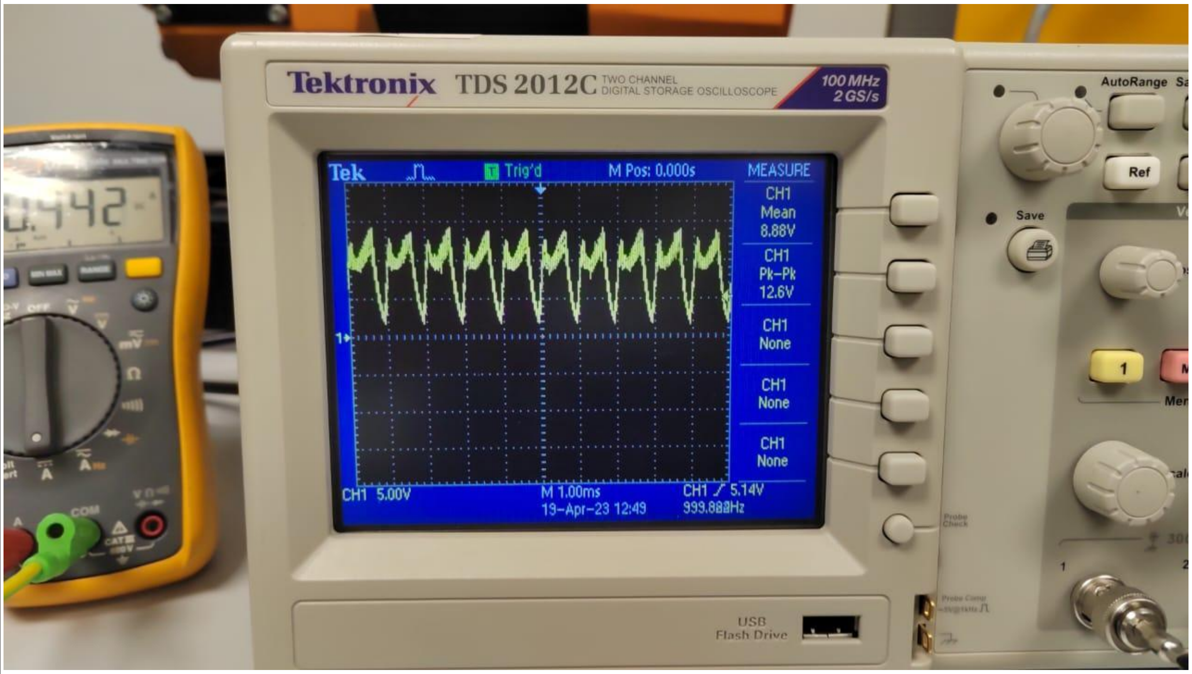


Figure 28 Output voltage waveform for C = 10.068μF and D = 0.7; y-axis is voltage (V) and x-axis is time (ms)

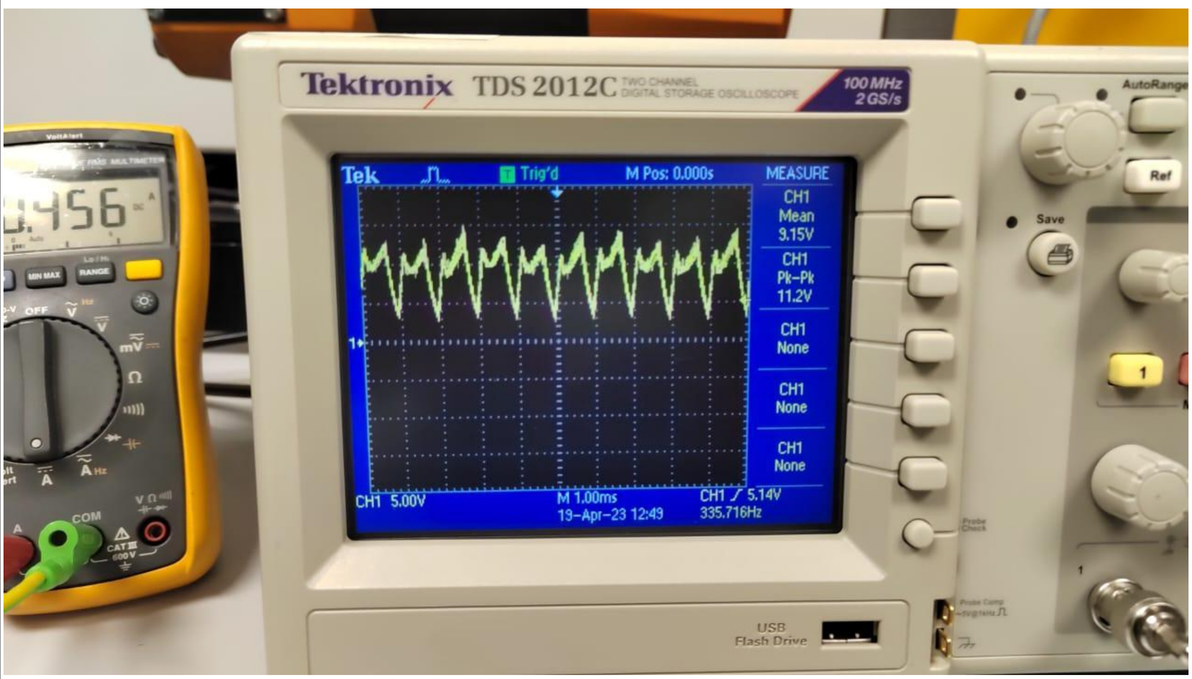


Figure 29 Output voltage waveform for C =13.408 μF and D = 0.7; y-axis is voltage (V) and x-axis is time (ms)

checked

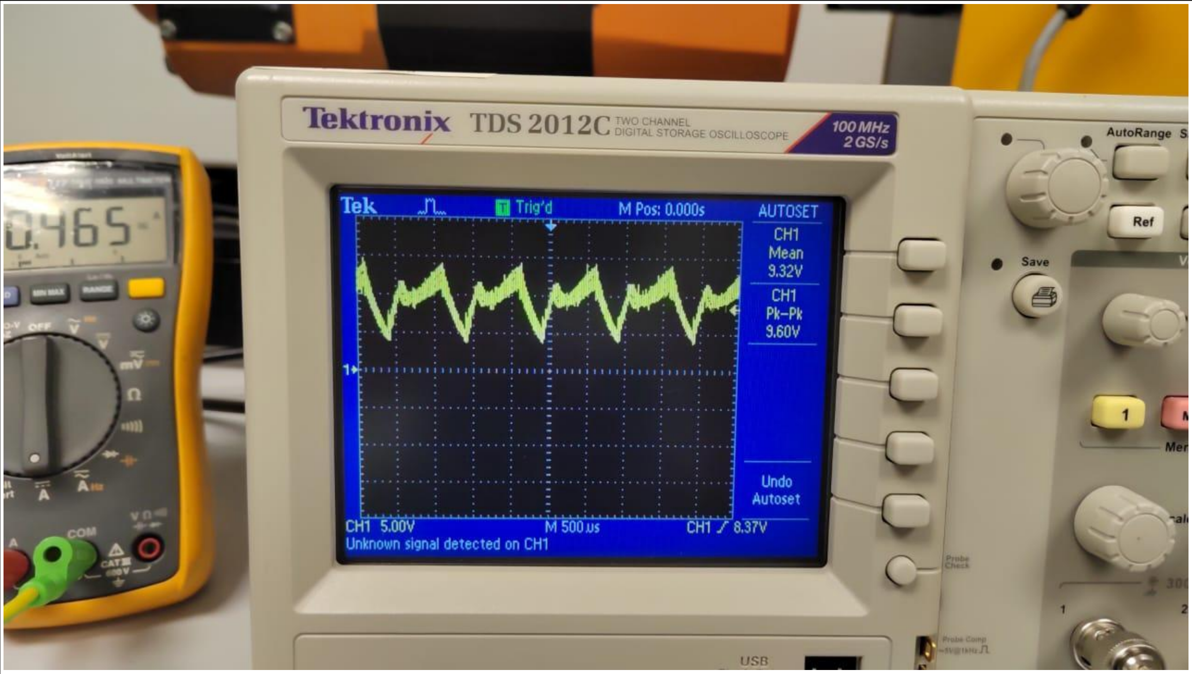


Figure 30 Output voltage waveform for C = 16.755µF and D = 0.7; y-axis is voltage (V) and x-axis is time (ms)

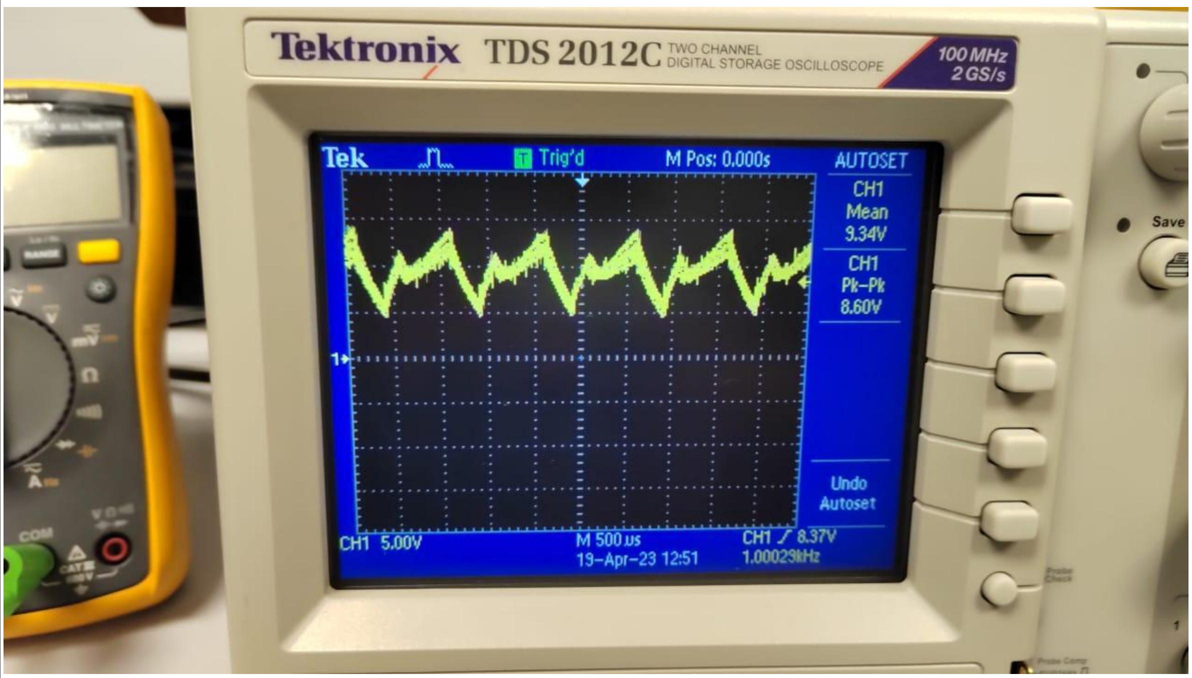


Figure 31 Output voltage waveform for C =20.11µF and D = 0.7; y-axis is voltage (V) and x-axis is time (ms)

Show the output voltage ripple waveform (from simulation) for each knob position [2 marks]

(Insert a picture of your output voltage ripple waveform (from simulation) for each knob position)

checked

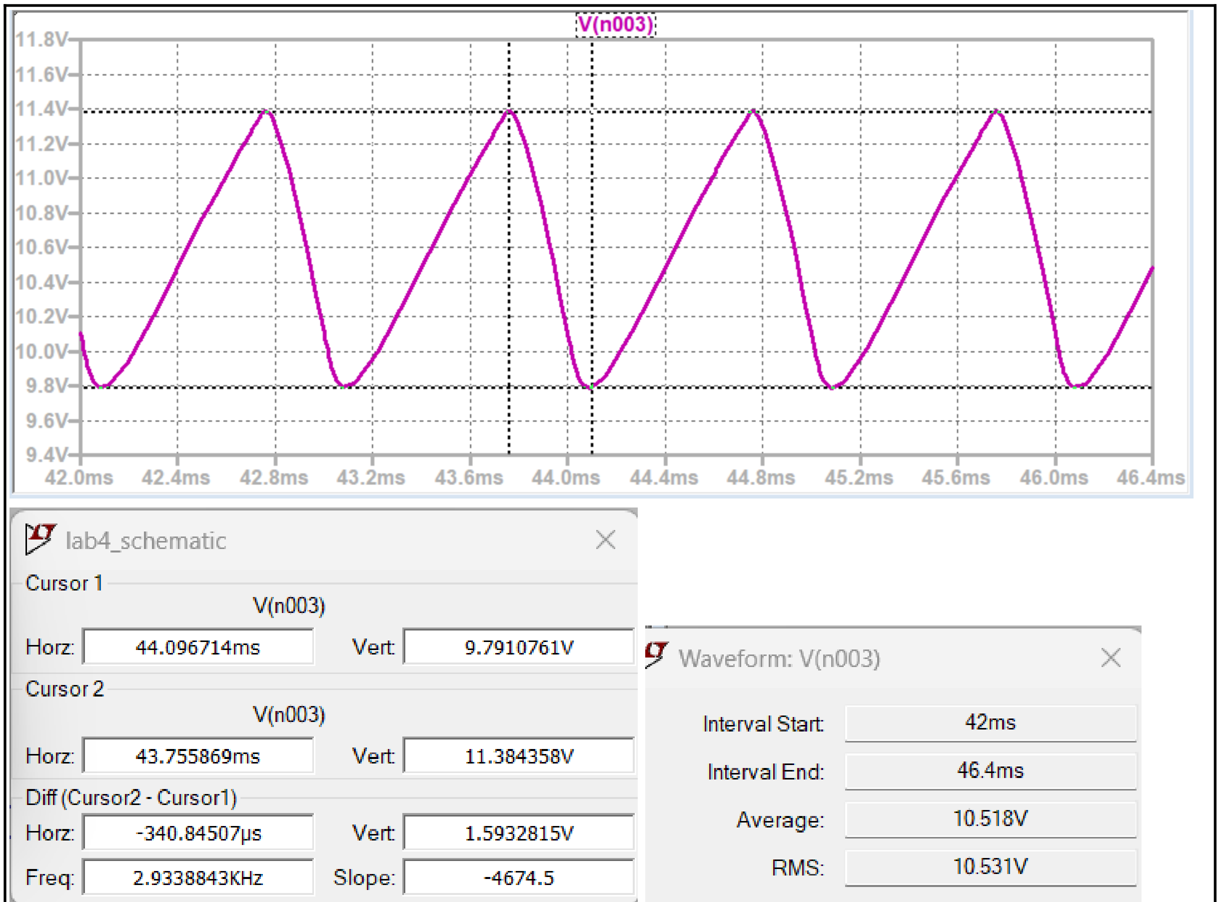
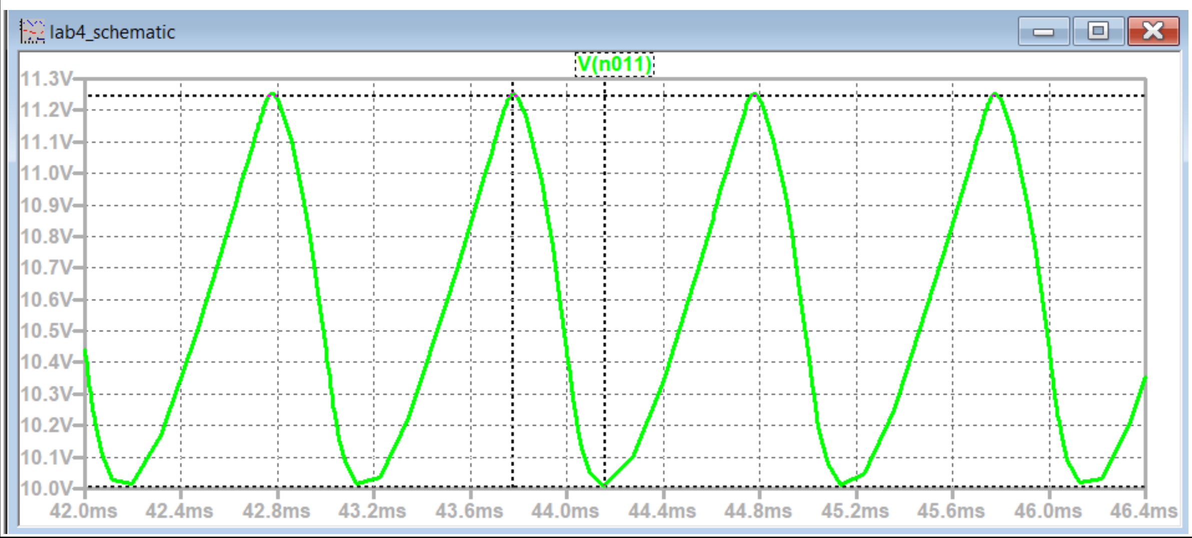


Figure 32 Output voltage waveform for C = 3.348µF and D = 0.7; y-axis is voltage (V) and x-axis is time (ms)



checked

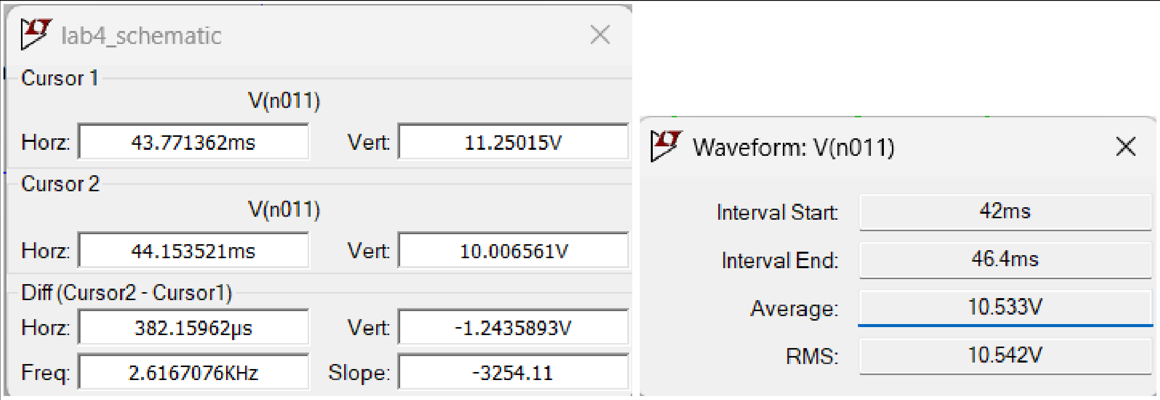


Figure 33 Output voltage waveform for C = 6.734µF and D = 0.7; y-axis is voltage (V) and x-axis is time (ms)

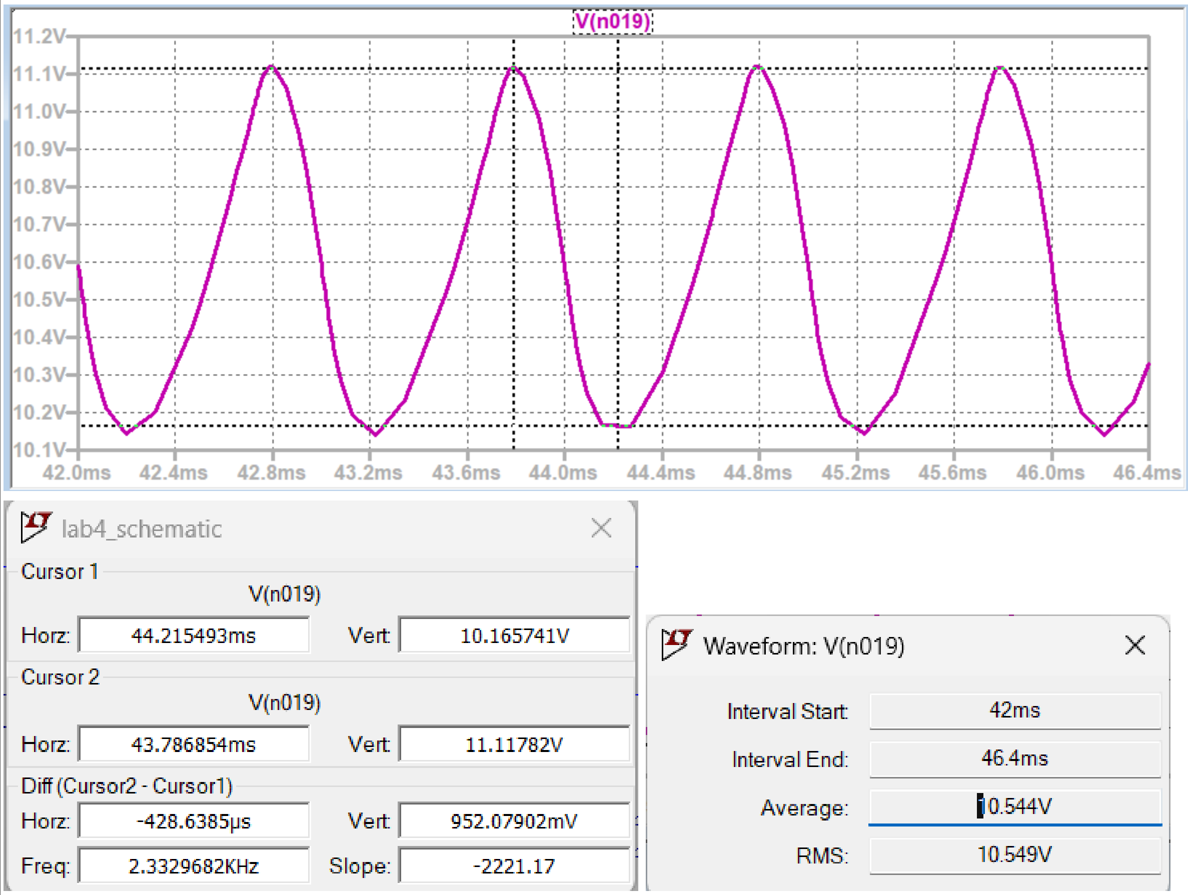


Figure 34 Output voltage waveform for C = 10.068µF and D = 0.7; y-axis is voltage (V) and x-axis is time (ms)

checked

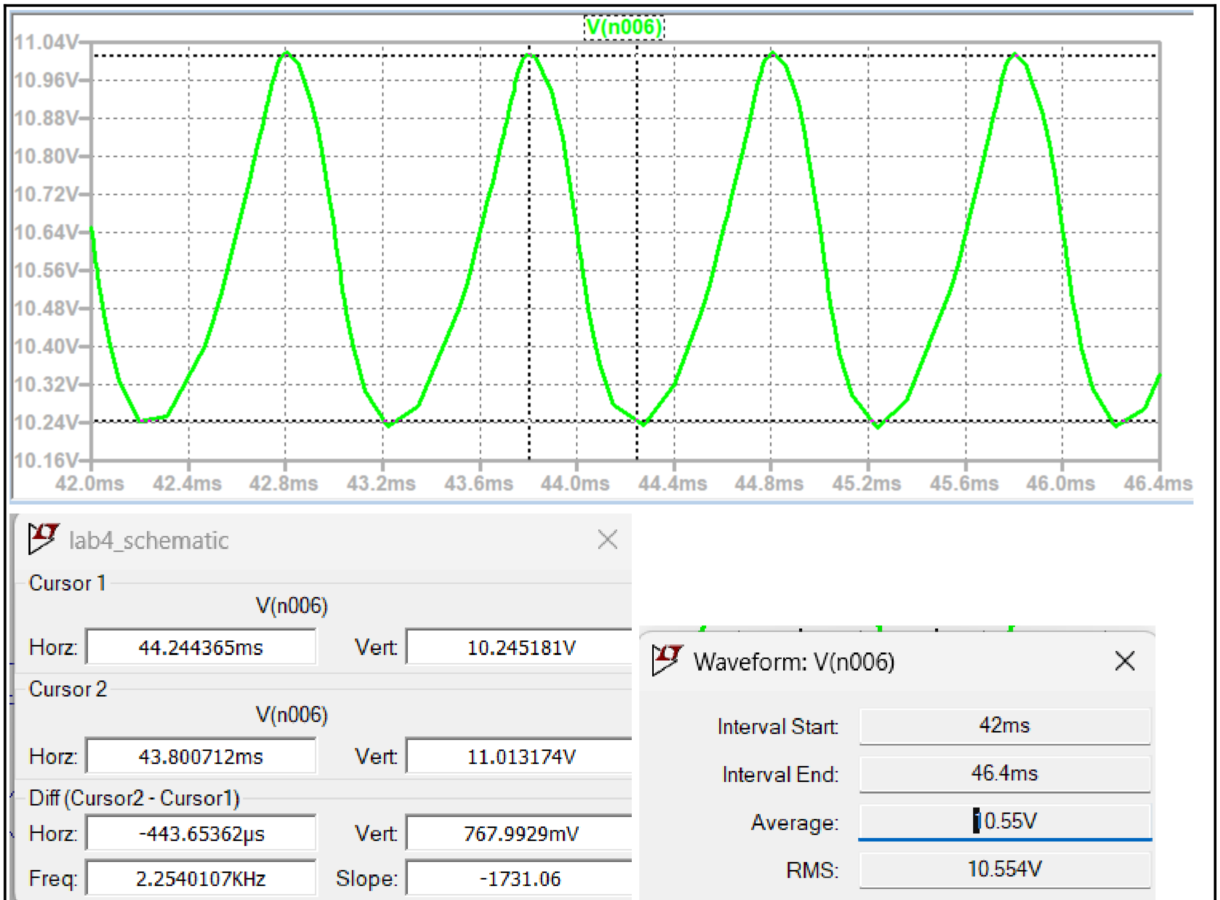
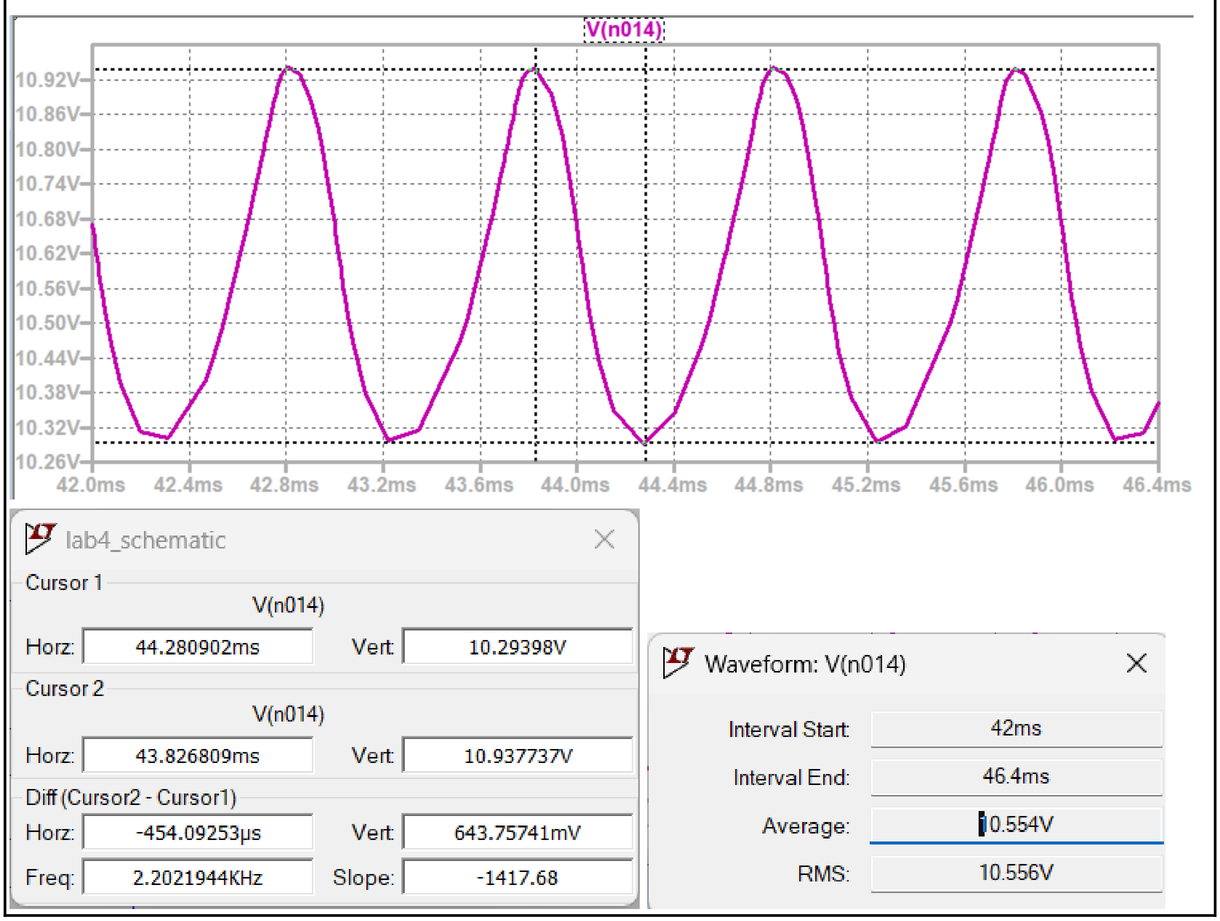


Figure 35 Output voltage waveform for C = 13.408µF and D = 0.7; y-axis is voltage (V) and x-axis is time (ms)



checked

Figure 36 Output voltage waveform for C = 16.755µF and D = 0.7

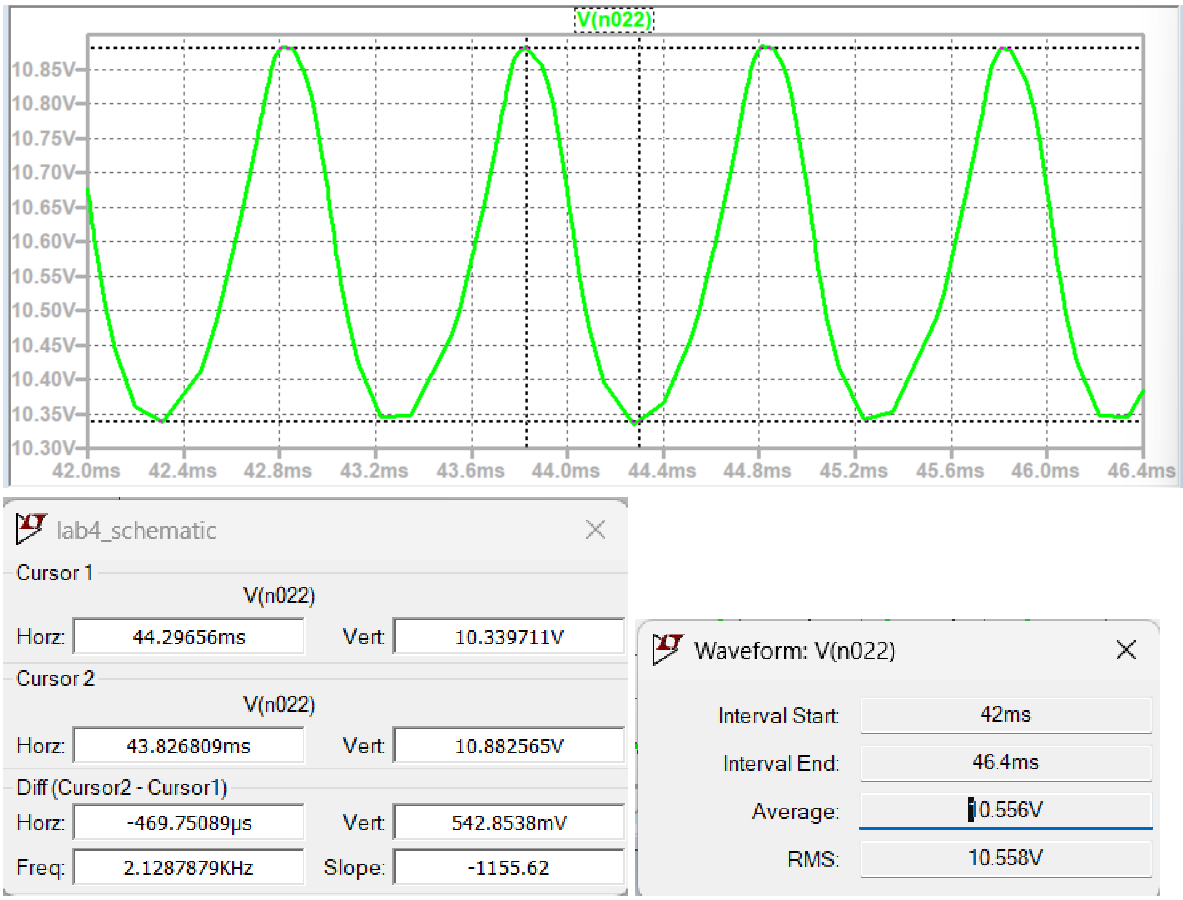


Figure 37 Output voltage waveform for C = 20.11µF and D = 0.7; y-axis is voltage (V) and x-axis is time (ms)

Analysis [20 Marks]

(Discuss the obtained results of average output voltage and output voltage ripple for duty ratio of 30%, 50% and 70% for each of the knob position of the capacitor load.)

<u>Change in Duty Cycle and change in output average Value</u>

For a duty cycle of 30%, our average output voltage starts from 3.1V and gradually increases up to saturation voltage of 4.03V as we increase the capacitance value. The simulated average output voltage remains constant at 4.25V.

For a duty cycle of 50%, our average output voltage starts from 5.26V and gradually increases up to saturation voltage of 6.9V as we increase the capacitance value. The simulated average output voltage remains constant at 7.66V.

For a duty cycle of 70%, our average output voltage starts from 8.16V and gradually increases up to saturation voltage of 9.58V as we increase the capacitance value. The simulated average output voltage remains constant at 10.556V.

Generally, the measured average output voltage is smaller than the theoretical value for each duty cycle. This can be justified as there will be internal voltage drop in the internal resistance of the wire connections, and the internal circuitry of the measurement equipment.

The simulated average output value is close to the theoretical average output voltage. The marginal differences can be attributed to the difference in buck converter circuitry on Spice and in the LMS module.

checked

There is a scenario that should be noted. The change in capacitance should not change the average output value. This is because taking the KVL of the buck-converter, the low pass filter and the load, it will be in this form

$$V_{out} = V_l + V_{load} V_{out} = L\frac{dI_l}{dt} + V_{load}$$

For an inductor circuit in steady state, the average output of the inductor would be equal to zero to prevent the build-up of voltage as shown in Figure 1.

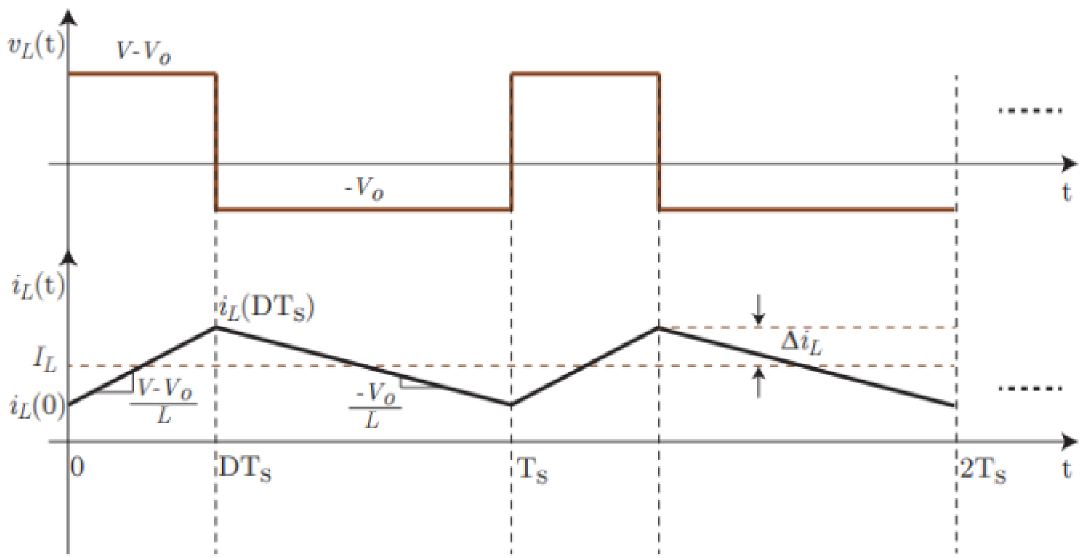


Figure 38 Graph of inductor voltage and inductor current

However, during the experiment, as the capacitance values changes, we notice that the capacitance starts off small, then increases closer to the theoretical values as we increase the capacitance value. This can be justified by assuming that the resistive has stray capacitance in series with it, which causes the additional voltage drop at low parallel capacitance, but becomes negligible as we increase the parallel capacitance value to it.

<u>*Change in Capacitance and change in output ripple voltage*</u>

As we increase the capacitance, the output ripple decreases for each duty cycle. This follows the inverse relationship that relates the output ripple voltage with the capacitance.

$$\Delta V_0 = \frac{(V - V_0)DT_s^2}{16LC}$$

The theoretical output ripple for a duty cycle of 30% ranges from 0.3099 – 2.0195 V. The theoretical output ripple for a duty cycle of 50% ranges from 0.3000– 0.8525V. The theoretical output ripple for a duty cycle of 30% ranges from 0.3573 – 2.709 V.

The simulated output ripple for a duty cycle of 30% ranges from *0.6 - 1.705 V*. The simulated output ripple for a duty cycle of 50% ranges from *0.3310- 1.0170V*. The simulated output ripple for a duty cycle of 70% ranges from *0.2715 – 0.7974V.*

The experimental output ripple for a duty cycle of 30% (obtained from the peak ranges from 7.8- 15.6*V*. The simulated output ripple for a duty cycle of 50% ranges from 8.8 - 16.8*V*. The simulated output ripple for a duty cycle of 70% ranges from 8.6- 17.4*V.*

The simulated and theoretical does not defer much at low duty cycles, but as the duty cycle increases, the differences between them increases. This can be attributed to the differences in buck converter circuitry between the Spice model and the LMS model.

There is a special scenario that should be taken note. The theoretical value and the actual output ripple differ by a very large margin (500% - 2000%). There are 2 possible explanations to this.

Theory 1: The cut-off frequency of the low pass filter is insufficient to filter off external noise and the output voltage ripple effectively. This could happen if the noise has a lower frequency than the cutoff frequency of the low pass filter.

checked

Theory 2: The cutoff frequency of the low pass filter is much higher than the switching frequency. Meaning the harmonics of the signal might be in the passband as well.
.

Discussion

1. Explain the relationship between duty cycle and the voltage ripple. [10 Marks]

Duty cycle is the ratio when the switch is ON to the total switching period. The voltage ripple is the fluctuation in output voltage due to the switching. It is given:

$$\Delta v_o = \frac{V - V_o}{16LC} D T_s^2$$

Substituting the equation for the average output voltage $V_0 = DV$,

$$\Delta v_o = \frac{V - DV}{16LC} D T_s^2$$

$$\Delta v_o = \frac{V(1 - D)}{16LC} D T_s^2$$

The relationship between the voltage ripple and the duty cycle is parabolic:

$$\Delta V_o \propto D(1 - D)$$

We will get the largest voltage ripple when D is 50%, and the voltage ripple decreases as the duty cycle increases / decreases from 50%.

2. List the difficulties encountered during the experiments. [3 Marks] Justify the differences between the measured and calculated values. [2 Marks] State whether the measured or calculated values are more accurate. [2 marks] For real practice, suggest procedures which can be carried out to prevent any measurement error(s). [3 Marks]

<u>Difficulties encountered</u>

- *A considerable amount of time was used to familiarize with the function generator. Our team struggled to generate the pulse in continuous mode with 1kHz frequency.*
- *The buck converter was pretty much a black-box in this experiment. We did not devise a way to measure the outputs of the buck converter to ensure it is correct. Therefore, we can only assume that the buck converter is functioning as expected and its output is 100% correct. However, there were great magnitude deviations in the CRO waveforms from the LTSpice waveforms, and we have no immediate explanation why this phenomenon occurred.*
- *The output voltage ripple value is not displayed in the CRO, and requires the value of the output voltage to calculate. This hinders us from performing instantaneous calculations and directly cross-checking the results.*

<u>Justification of differences between measured and calculated values</u>

- *The internal dynamics of the real-life buck converter circuit differs from the ideal model.*
- *The cut-off frequency of the low pass filter in the buck converter is higher than the frequency of the noise. The noise can introduce oscillations and offsets in the waveform, which is observed in our results.*
- *The cut-off frequency of the low pass filter is higher than the switching frequency and its harmonics. Similarly, this may introduce oscillations in the waveform, which is observed in our results.*
- *The inductance in the circuit is actually not known, we just assumed it to be 33mH.*

checked

- *Internal resistance and stray capacitance/inductance in real-life components are not accounted for in calculations.*
- *Thermal, Shot, and Flicker noise inherent in circuit design.*
- *Pulse frequency fed to the buck converter might need to be higher (eg. 1 MHz instead of 1 kHz)*

Which values are more accurate?
The calculated values are more accurate because:
- *The calculated values are analytical approaches, formulas derived from fundamental laws of physics. These equations model the actual phenomenon to a high level of accuracy.*
- *Some of the calculated values were obtained through simulation. LTSpice models the solution space and solves it with respect to time. The accuracy of performing such calculations repeatedly provides insight into the transient response of the system.*

Real-life practices to prevent measurement errors
- *Calibration of measurement devices to reduce the likelihood of systematic errors.*
- *Repeat the experiment and take the average to reduce the likelihood of human errors.*
- *Perform simulations beforehand and plot the expected output. During the experiment, we can then immediately compare the measured output to the theoretical output. This gives us assurance that the results are correct if the outputs are similar; and prompt us to re-check our experimental setup if they are not.*
- *Ensure the frequency input to the system is correct (ie. a system may behave differently for various frequencies, described by the frequency response of the system)*

Conclusion and Findings *[14 Marks]*

The objective of this experiment is to comprehend the operation of a DC-DC buck converter. The two manipulated variables in this experiment are the duty cycle percentage of the commutation cell & the value of capacitance for the capacitor used in the buck converter. The arbitrary function generator controls the duty cycle ratio whilst the three-phase capacitor load bank supplies the capacitance needed. The capacitor load bank comprises a switch to turn the load on or off. Additionally, a capacitance-controlled knob is present to adjust the capacitance value of the load.

The duty cycle ratio is adjusted to obtain percentages of 30%, 50%, and 70%. The capacitance-controlled knob (variable capacitor) is rotated 6 times to alternate through 6 capacitance values: 3.348, 6.734, 10.068, 13.408, 16.775 and 20.110 (μF). The following steps were taken to conduct the experiment:
1) *The DC power supply was turned on and set to provide a voltage of 15 V*
2) *The arbitrary function generator was switched on with following settings:*
   Duty ratio: 30%, Waveform: Pulse, Mode: Continuous, Frequency: 1kHz, Amplitude: 5V, Offset: 2.5V
3) *The capacitive load was turned on, and the knob was set to '1' (3.348 μF)*
4) *The average output voltage was measured using a digital multimeter*
5) *The output ripple voltage was measured using a Cathode Ray Oscilloscope (CRO)*
6) *WIth the same settings, the capacitor-controlled knob was rotated 5 more times to cycle through increasing capacitance values.*
7) *Steps 2 to 6 were repeated using duty ratios of 50% and 70%*

The output voltage is given by:

$$V_o = DV$$

where V_o is output voltage, D is duty ratio, V is input voltage. V_o is directly proportional to D when V is constant. Thus, when duty cycle increases, the output voltage increases as well. Our measurements comply with this theoretical analysis. The output voltage ripple, Δv_o can also be approximated to $\Delta v_o = (D - D^2)$ when all other parameters are constant. The equation is visualized in the following graph:

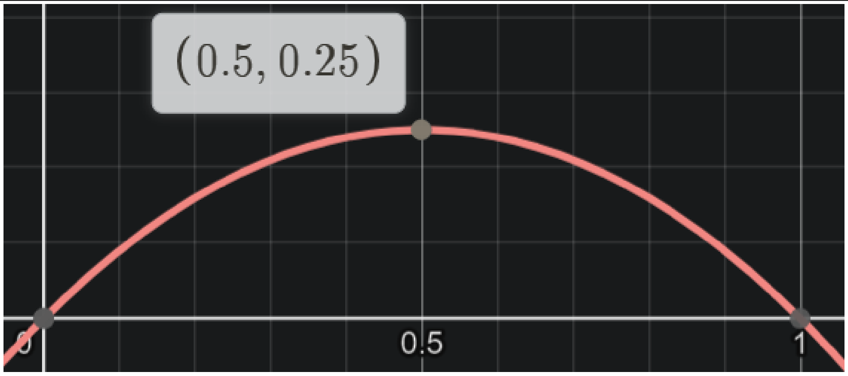


Figure 38 Illustration of voltage ripple generated using DESMOS Graph

As we can see observe, the relationship between Δv_o and D is a negative quadratic graph with a maximum point. The output ripple voltage peaks when the duty cycle ratio is exactly 50%. The ripple voltage measurements from the experiment complement this analysis. Finally, we observe that the output ripple voltage value diminishes as the capacitance value rises. This relationship can be made sense through the equation that follows:

$$\Delta v_o = \frac{(V - V_o)DT^2}{16LC}$$

whereby we can observe that the output ripple voltage is inversely proportional to capacitance. The 3 relationships analyzed theoretically align with the practical measurements.

We were able to investigate how various factors impact the output results of a DC-DC buck converter. The manipulated variables were the duty ratio and capacitance, whilst the responding variables were the output ripple voltage and average output voltage. The experiment has improved our knowledge of how each factor affects the functionality and efficacy of the DC-DC Buck Converter.

***References** [6 Marks]*

(Include minimum 3 references here)

[1] B. Bahrani. (2022). ECE3051 – DC-DC Buck Converter [PDF]. Available: https://lms.monash.edu/course/view.php?id=133062&section=26
[2] Hart, Daniel W. (2011). Power Electronics International ed. McGraw-Hill.
[3] A. W. Cristri and R. F. Iskandar, “Analysis and Design of Dynamic Buck Converter with Change in Value of Load Impedance,” Procedia Engineering, vol. 170, pp. 398–403, 2017, doi: https://doi.org/10.1016/j.proeng.2017.03.064.
[4] “What is Buck Converter? Operating Principle and Waveform Representation of Buck Converter,” Electronics Coach, Sep. 15, 2021. https://electronicscoach.com/buck-converter.html
[5] P. Falkowski, “Analysis and design of high efficiency DC/DC buck converter,” PRZEGLĄD ELEKTROTECHNICZNY, vol. 1, no. 5, pp. 158–163, May 2016, doi: https://doi.org/10.15199/48.2016.05.29.

in text citation not found (minus 3 marks)

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******** *THE END* *******

checked

SCHOOL OF ENGINEERING

ELECTRICAL AND COMPUTER SYSTEMS ENGINEERING

LABORATORY REPORT MARKING RUBRIC

ECE3051: ELECTRICAL ENERGY SYSTEMS

Experiment Number: 5

Title of Lab Sheet: Synchronous Machine

Group Number: 8

No.	Student ID	Name of Group Members	Total Marks
1	30720230	Loh Jia Quan	99/100
2	31106889	Agill Kumar Saravanan	99/100
3	30719305	Huan Meng Hui	99/100
4	32194471	Tan Jin Chun	99/100
5	32259417	Chong Yen juin	99/100

MARKS BREAKDOWN

Section	Total Score	Actual Marks	Scoring Band	Criteria	Comment
Results	40		30-40	Clear and completely labelled figures of the experiment/simulation results with justifications and tables. A detailed caption is provided for each figure with an in-text figure reference. The x-axis and y-axis are labelled with the unit in the bracket. The legend is provided whenever it is deemed to be required. If there is more than one line, the lines should be clearly distinguishable with the visible difference such as dotted line, dashed line and solid line, even in black and white.	39
			20-30	Some of the figures of the experiment/simulation setup are not clear, do not have any labelling/ caption/ in-text caption reference/ distinguishable multiple lines and are blurry. The table and justification have mistakes or errors.	
			0-20	Insufficient amounts of figures and labelling of the experiment/simulation layout setup, which is not correct and/or unclear. The table is not filled.	
Discussion	40		30-40	Complete data collection and presentation using tables/figures/ graphs with appropriate labels. Discussion of the results with prudent judgment. Have a comparison of the measured results with theoretical values and in-text citations from the peer-reviewed references. The comprehensive comparison, evaluation and justification of the results are given with clear explanation to demonstrate the understanding of the laboratory.	40
			20-30	The discussion shows little understanding of what the experiment/simulation is all about. Brief comparison, evaluation and justification of the results, with unclear/ incorrect explanation on the theoretical and experimental/ simulation results.	
			0-20	Only restatement of the results without commenting on the expected key points.	

				Incorrect judgment/ arguments were used. No comparison, evaluation and justification of the results, with an unsatisfactory explanation on the theoretical and experimental/ simulation results.	
Conclusion, References and Appendix	20		15-20	Explained how the aims of the experiment have been achieved. The key features of the methods used, the most important results and the findings of the laboratory have been summarized. Complete references list to any book, articles and websites is provided with proper in-text citations in correct formatting. The appendix is provided in detail.	20
			10-15	A conclusion is drawn but is not supported by the experimental/ simulation evidence and a clear understanding of the findings. Incomplete references to the books or any other sources used in the report and the in-text citations are inappropriate or incorrect. The appendix is partially provided.	
			0-10	No sensible conclusion. The referencing is presented in the wrong format. No evidence, attachments, appendices are attached. Irrelevant referencing was used. Unclear understanding of the experiment without a summarized conclusion and the evidence of results. No appendix is provided.	
Total	100				99

Examiner/ Assessor of ECE3051: Electrical Energy Systems
Date: 19/5/2023

EXPERIMENT 5

SYNCHRONOUS MACHINE

Characteristics of a three-phase synchronous generator

1. Preliminary

Nameplate data for the machines [8 Marks]

(Insert a picture or table showing the nameplate data of the synchronous and DC machine used in this experiment)

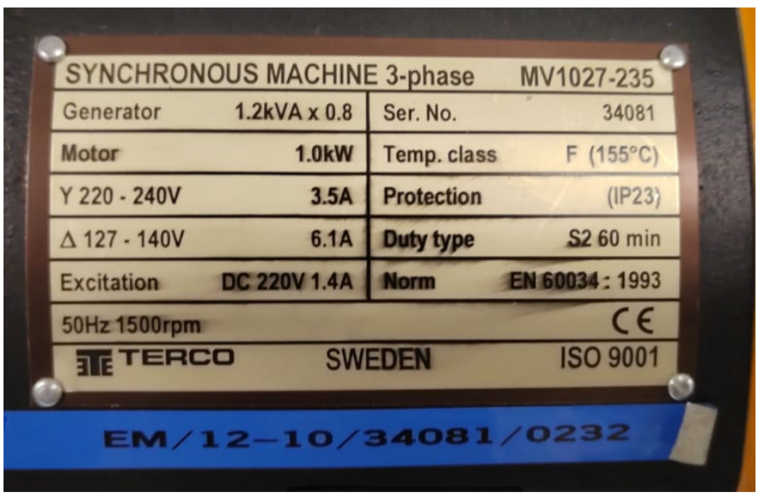

Fig. 1. Nameplate data of synchronous machine

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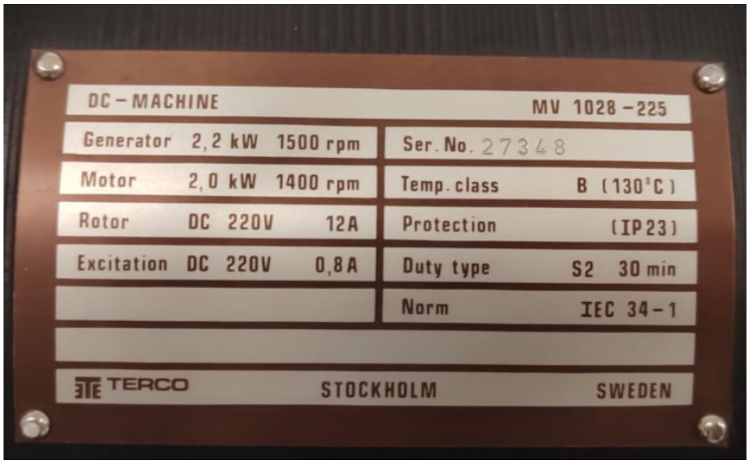

Fig. 2. Nameplate data of DC machine

Experimental wiring and experimental setup [8 Marks]

(Insert a picture of your experimental setup and label all the equipment used.)

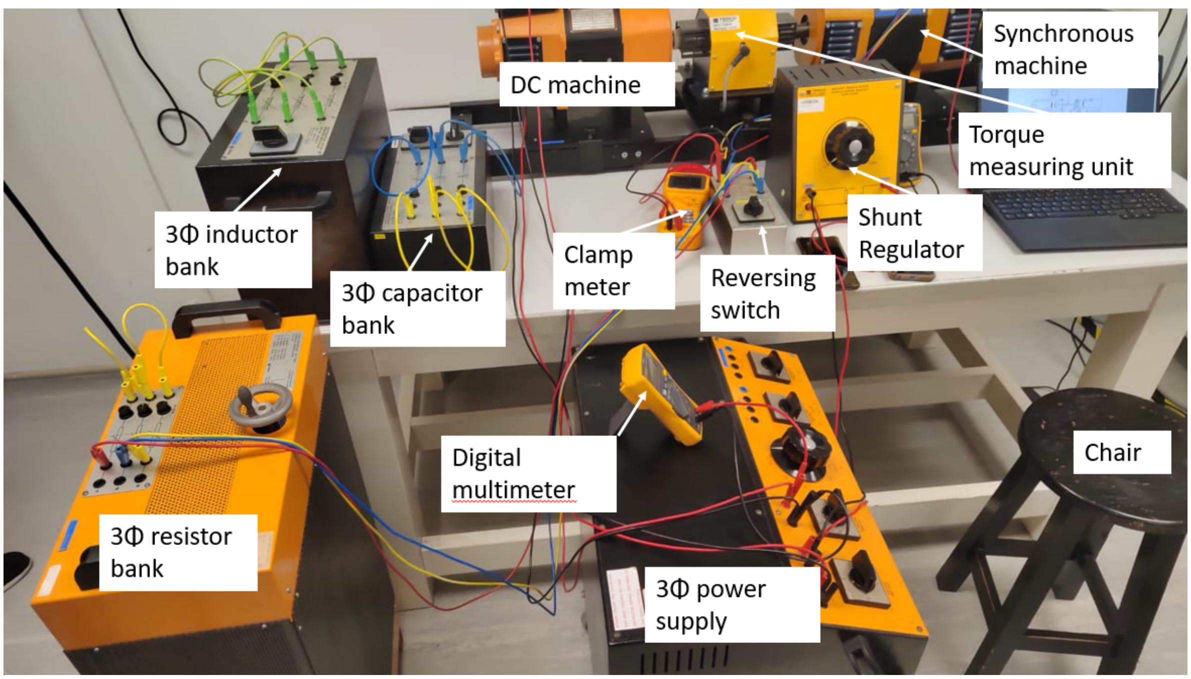

Fig. 3. Experiment Setup

2. No-load test [6 Marks]

(Fill up the necessary data/ measurements from the experiment into the table below.)

checked

Excitation current, I_m (A)	Stator induced voltage, U (V)
0.004	3.068
0.053	13.90
0.101	25.74
0.150	52.00
0.202	71.90
0.251	90.10
0.302	107.90
0.351	126.40
0.400	143.80
0.450	159.80
0.501	175.30
0.550	191.90
0.600	206.20
0.653	220.30
0.701	233.40
0.750	246.20
0.801	256.70
0.850	268.20
0.900	277.30

3. Short-circuit test [6 Marks]

(Fill up the necessary data/ measurements from the experiment into the table below.)

Excitation current, I_m (A)	Armature current, I_A (A)
0.001	0.21
0.049	0.47

checked

0.101	0.82
0.148	1.20
0.205	1.53
0.251	1.90
0.301	2.30
0.350	2.62
0.402	3.07
0.449	3.30

checked

Load test

Resistive load [5 Marks]

(Fill up the necessary data/ measurements from the experiment into the table below.)

Excitation current, I_m (A)	**Armature current, I_A (A)**	**Stator induced voltage, U (V)**
0.676	0.56	220.7
0.662	0.60	216.8
0.659	0.70	214.2
0.656	0.80	211.7
0.654	0.90	208.9
0.652	1.00	206.7
0.650	1.10	205.6
0.649	1.20	203.5
0.648	1.30	200.4
0.646	1.40	200.1
0.645	1.50	198.4
0.644	1.60	196.2
0.643	1.70	194.6
0.642	1.80	190.8
0.641	1.90	187.5
0.641	2.00	185.5
0.640	2.10	183.0
0.639	2.20	182.1
0.638	2.30	180.1
0.637	2.40	176.8
0.637	2.50	173.4

checked

0.637	2.60	171.7
0.637	2.70	167.5
0.636	2.80	166.0
0.635	2.90	162.9
0.635	3.00	161.2
0.635	3.10	158.6
0.635	3.20	154.9
0.635	3.30	153.1

Inductive load [5 Marks]

(Fill up the necessary data/ measurements from the experiment into the table below.)

Excitation current, I_m (A)	**Armature current, I_A (A)**	**Stator induced voltage, U (V)**
0.638	**0.62**	**198.2**
0.637	**1.00**	**181.2**
0.637	**1.31**	**167.4**
0.637	**1.60**	**151.3**
0.637	**1.83**	**140.4**
0.637	**2.00**	**132.8**
0.637	**2.20**	**123.0**
0.636	**2.40**	**116.8**
0.635	**2.55**	**108.5**
0.635	**2.65**	**102.7**

checked

0.635	**2.75**	**98.0**

Capacitive load [5 Marks]

(Fill up the necessary data/ measurements from the experiment into the table below.)

Excitation current, I_m (A)	**Armature current, I_A (A)**	**Stator induced voltage, U (V)**
0.636	0.59	237.5
0.636	1.08	254.9
0.635	1.74	271.8
0.635	2.37	289.3
0.635	**3.07**	**306.1**

checked

Discussion

a. Graphs of the no-load characteristic and short-circuit characteristic (Joshua)

[2 Marks]

(Insert the graphs of the no-load characteristic and short-circuit characteristic in the same diagram and with common I_m axis.)

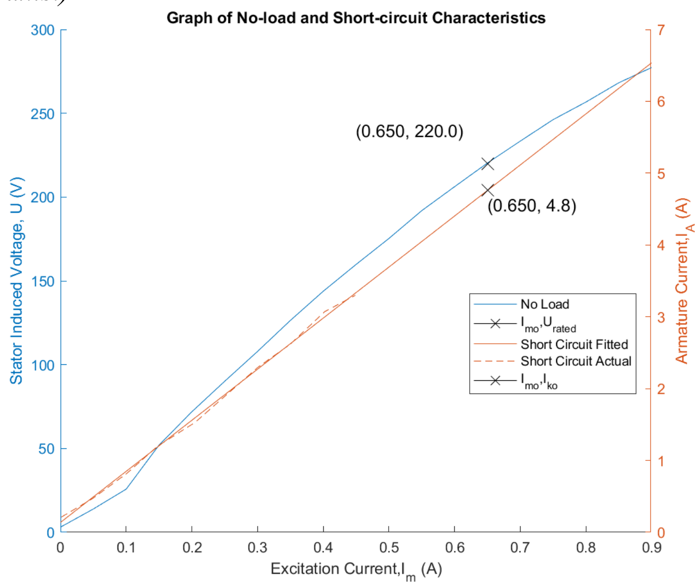

Fig. 4. Graph of no-load, short-circuit characteristic. Y-axis is Stator Induced Voltage, U (V) and X-axis is Excitation Current, I_m (A)

b. Graphs of the three load characteristics [3 Marks] (JQ)

(Insert graphs of the three load characteristics in the same diagram and with common I_A axis.)

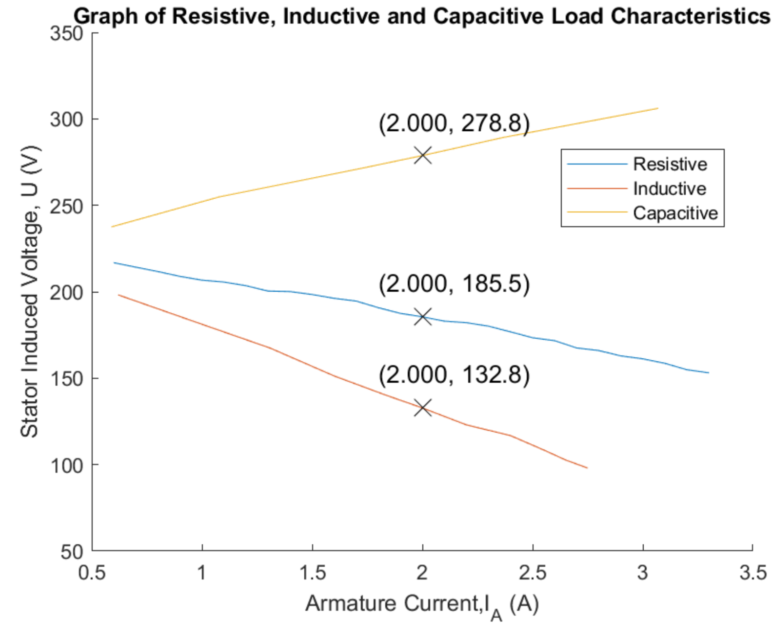

Fig. 5. Graph of resistive, inductive, capacitive load characteristics; Y-axis is Stator Induced Voltage, U (V) and X-axis is Armature Current, I_A (A)

c. No-load characteristic and the excitation current [2 Marks] (Joshua)

(Read and state the excitation current I_{mo} corresponding to the rated voltage (220V) from the graph above.)

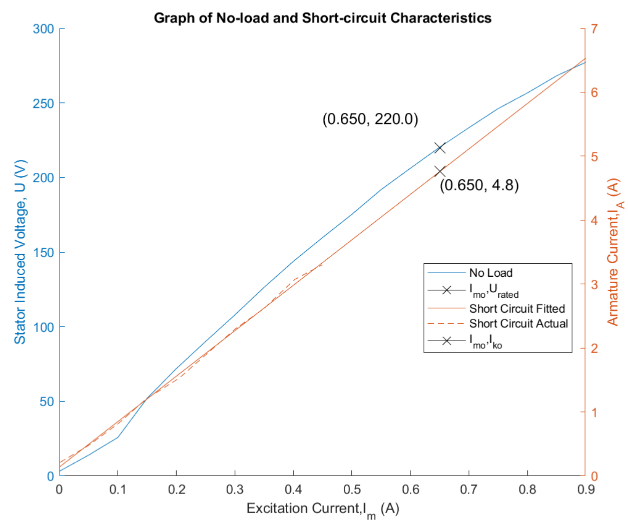

Fig. 6. Graph of no-load, short-circuit characteristic. Y-axis is Stator Induced Voltage, U (V) and X-axis is Excitation Current, I_m (A); Read graph to obtain the excitation current

Excitation current I_{mo} corresponding to the rated voltage 220V obtained from the no-load characteristic graph is 0.65A.

d. Short-circuit characteristic and the short-circuit current [2 Marks] (Joshua)

checked

(Read and state the short-circuit current I_{ko} obtained at the excitation current I_{mo} from the graph above.)

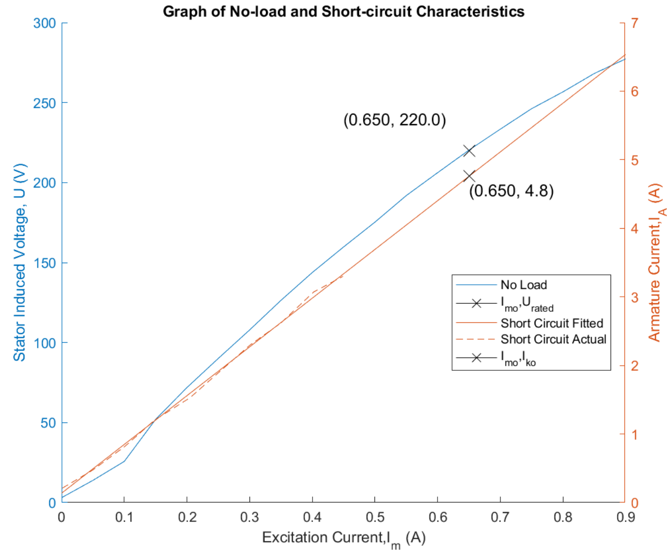

Fig. 7. Graph of no-load, short-circuit characteristic. Y-axis is Stator Induced Voltage, U (V) and X-axis is Armature Current, I_A (A); Read graph to obtain the excitation current and short circuit current

As our readings were unable to obtain the short-circuit current at the rated excitation current without exceeding the rated short-circuit current (3.5A), the current graph has to be interpolated.
Short-circuit current I_{ko} corresponding to the excitation current I_{mo} obtained from the interpolated no-load characteristic graph is 4.8A.

e. Synchronous reactance of the generator per phase [2 Marks] (Joshua)

(Calculate the synchronous reactance of the generator per phase as $X_s = U_n/I_{ko} = 127/I_{ko}$ Ω/phase.)

$$X_s = \frac{U_n}{I_{ko}} = \frac{\Omega}{phase} X_s = \frac{127}{4.8} = 26.46\frac{\Omega}{phase}$$

f. Short-circuit ratio of the generator [2 Marks] (Joshua)

(Calculate the short-circuit ratio of the generator $k_c = I_{ko}/I_n$, where I_n = rated current of the generator.)

$$K_c = \frac{I_{ko}}{I_n} = \frac{4.8A}{3.5A} = 1.37A$$

wrong unit (minus 1 mark)

checked

g. Three vector diagrams [2 Marks]

(Draw three vector diagrams to scale with E = 127 V, I_A = 2 A and φ = 0°, +90° and -90°, respectively. The numerical value of X_s can be obtained from part e.)

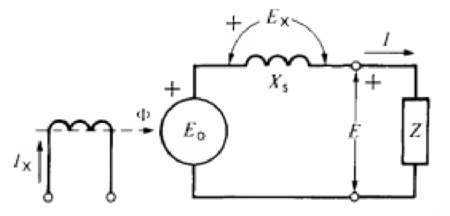

Fig. 8. Equivalent Circuit of Synchronous Generator

$$Xs = 26.46 \frac{\Omega}{phase}$$

A. Resistive Load

$$I = 2\angle 0° A$$

$$E_{terminal} = 127\angle 0° V$$

$$E_x = I * jXs = 2 * j26.46 = j52.92\, V$$

$$Stator\ Induced\ Phase\ Voltage,\ E_0 = E + E_x = 127 + 52.92j = 137.58\angle 22.62°\, V$$

$$Stator\ Induced\ Line\ Voltage,\ U = E_0 * \sqrt{3} = 238.303\angle 22.62°\, V$$

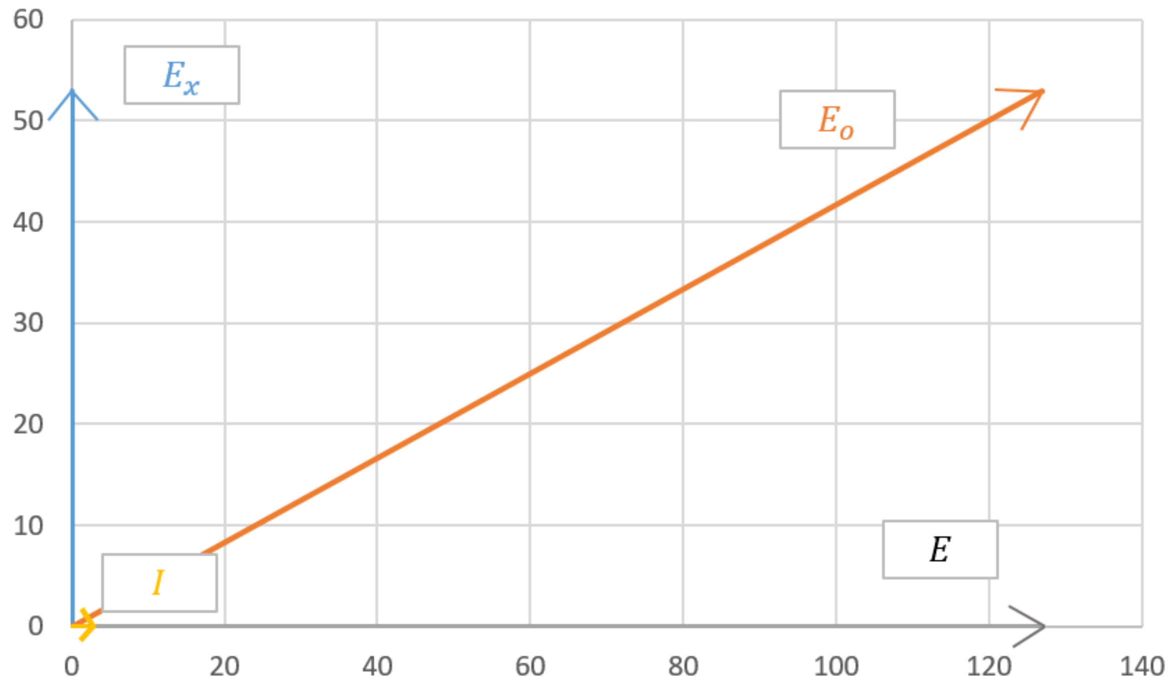

Fig. 9. Vector diagram of Resistive Load

checked

B. *Inductive Load*

$I = 2\angle - 90°A$

$E = 127\ \angle 0°V$

$E_x = I * jXs = 2\angle - 90° * j26.46 = 52.92\ V$

$Stator\ Induced\ Voltage_{Phase},\ E_0 = E + E_x = 127 + 52.92 = 179.92\ V$

$Stator\ Induced\ Line\ Voltage,\ U = E_0 * \sqrt{3} = 311.63\ V$

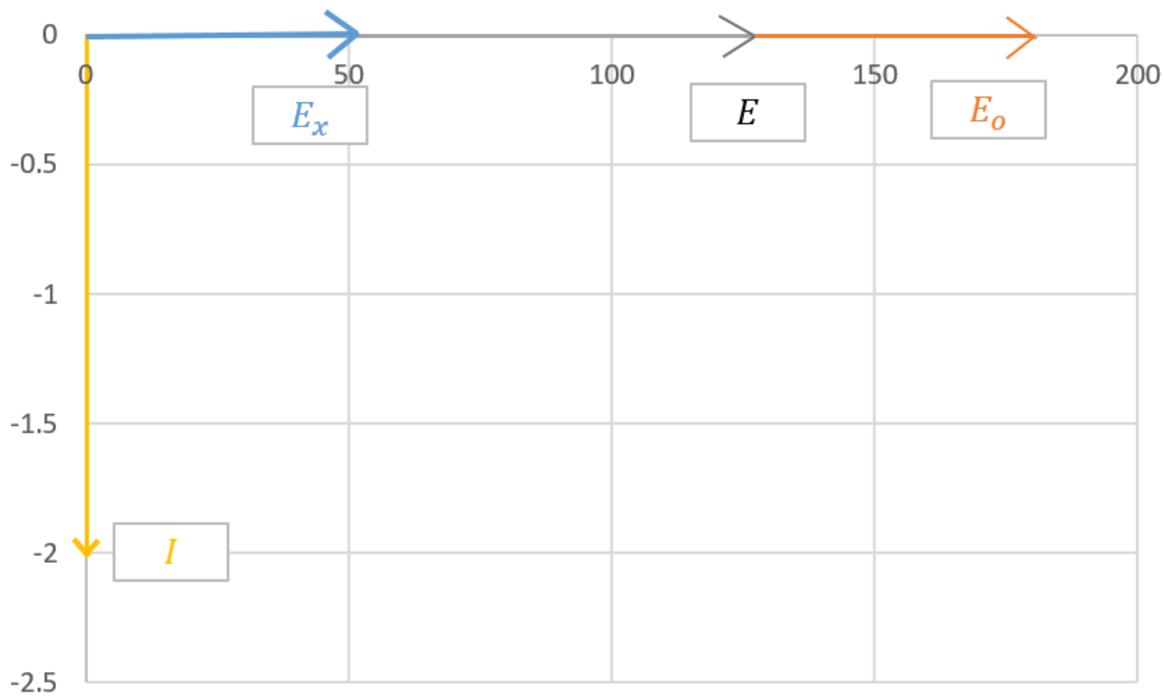

Fig. 10. Vector diagram of Inductive Load

C. *Capacitive Load*

$I = 2\angle 90°\ A$

$E = 127\ \angle 0°\ V$

$E_x = I * jXs = 2\angle 90° * j26.46 = \ - 52.92\ V$

$Stator\ Induced\ Voltage_{Phase},\ E_0 = E + E_x = 127 - 52.92 = 74.08\ V$

$Stator\ Induced\ Line\ Voltage,\ U = E_0 * \sqrt{3} = 128.31\ V$

checked

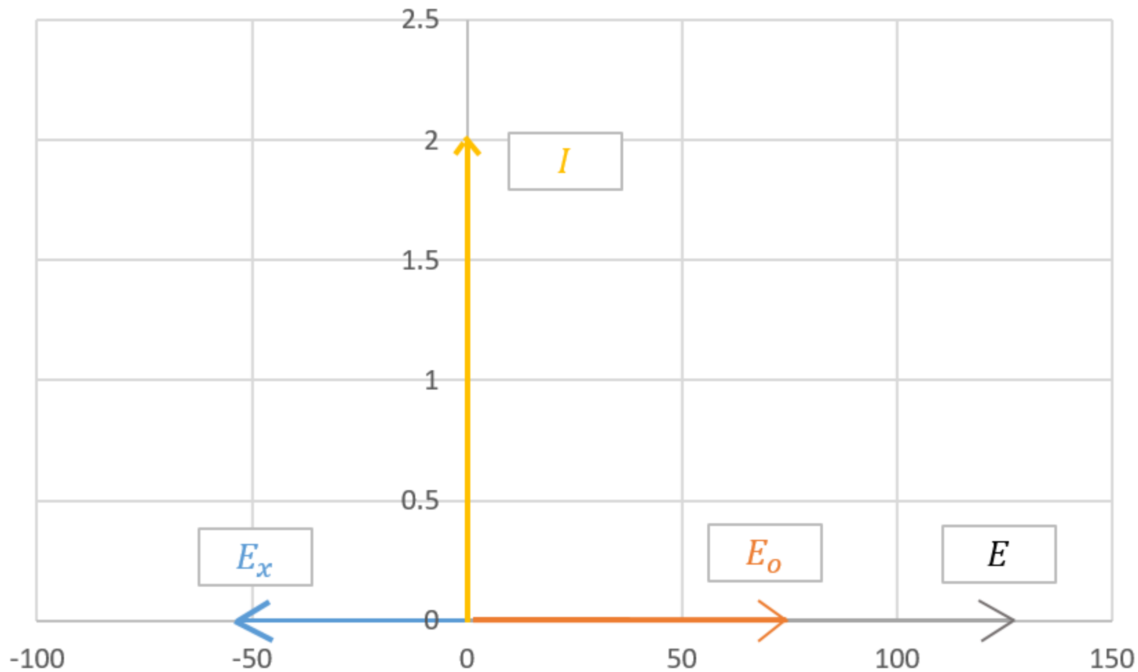

Fig. 11. Vector diagram of Capacitive Load

h. Comparison of vector diagrams with the corresponding values on the load characteristic [2 Marks]

(Read U in the vector diagrams and compare with the corresponding values on the load characteristic.)

	Armature current, I_A (A)	*stator induced phase voltage, U (V)*	*stator induced line voltage U_{line} (V)*
Resistive Load	*2*	*137.58*	*238.303*
Capacitive Load	*2*	*74.08*	*128.31*
Inductive Load	*2*	*179.92*	*311.63*

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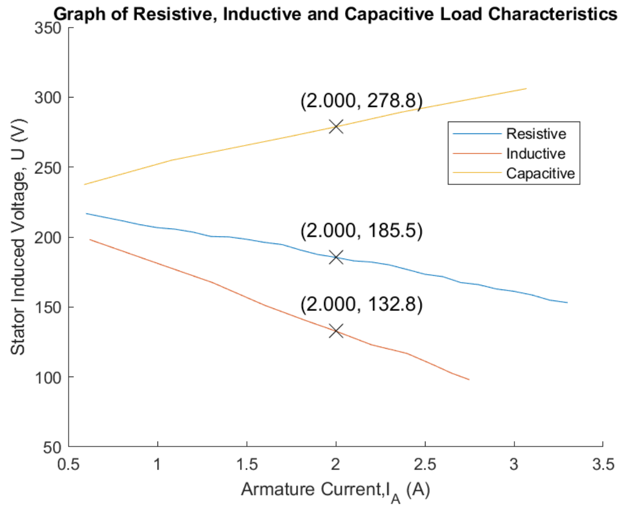

Fig. 12. Graph of R, L, C load characteristics, read graph to obtain U

	Armature current, I_A (A)	*stator induced phase voltage, U (V)*	*stator induced line voltage U_{line} (V)*
Resistive Load	*2*	*107.10*	*185.5*
Capacitive Load	*2*	*160.97*	*278.8*
Inductive Load	*2*	*76.67*	*132.8*

Comparison

	Armature current, I_A (A)	*stator induced phase voltage, U (V)*		*stator induced line voltage U_{line} (V)*	
		Vector	*Graph*	*Vector*	*Graph*
Resistive Load	*2*	*137.58*	*107.10*	*238.303*	*185.5*
Capacitive Load	*2*	*74.08*	*160.97*	*128.31*	*278.8*
Inductive Load	*2*	*179.92*	*76.67*	*311.63*	*132.8*

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The values of stator induced phase voltage, U, read from the phasor diagram have discrepancies with the experimental value read from the graphs.

One specific reason for the discrepancies between the phasor diagram and the experimental values is ***voltage regulation*** in the synchronous generator, the terminal voltage will change when the type of load changes.

The phasor diagram, in our calculation, assumes a constant terminal voltage (127V phase voltage), , leading to significant discrepancies in the results.

In our experimental setup, when the load is inductive, the stator induced voltage (read from graph) is the smallest because the terminal voltage will decrease as the armature current increases, as shown by the equation below
$U = E + E_x$; When E decreases, U will also decrease.

When the load is capacitive, the stator induced voltage will increase significantly (from graph) and become the largest in this experimental setting - as the armature current increases, the terminal voltage will increase. The relationship is trivial as shown above.

When the load is switched to resistive, the stator induced voltage (from graph) will decrease, but not as much as that of inductive loads'. This is because terminal voltage will decrease by a small margin as the armature current increases, albeit not to the same magnitude as inductive load.

That is the reason for the difference in values of phasor diagram and graph values, the changes of terminal voltage are not taken into account for computing the stator induced voltage as armature current varies.

checked

Discussion

1. Explain in detail the purpose of no-load, short-circuit and load test conducted in this experiment. [10 Marks]

The tests that are conducted in this experiment to describe the behavior of a real synchronous generator, that is the relationship between the excitation current, armature current and stator induced voltage when there is open-circuited, short-circuited, and connected with different types of load which are the resistive, capacitive and inductive load.

No-load test

The purpose of the no-load test is to determine the nominal excitation current at the specified stator voltage . In this test, the generator is operated at rated speed with no load connected to it. The field current is gradually increased, and the corresponding values of open-circuit voltage and field current are recorded. The open-circuit characteristic is a plot of the open-circuit voltage versus field current, and it provides information on the magnetization characteristics of the generator. The no-load test is essential for determining the generator's voltage regulation and for designing the excitation system. The no-load test is carried out to determine the open-circuit characteristic (also known as the saturation curve) of the synchronous generator. The nominal excitation current at the specified stator voltage even when the synchronous motor's magnetization characteristic may not be linear. The no-load test can also be used to determine the best excitation current for the short circuit test and the no-load impedance in the synchronous generator [2].The no-load test is conducted with the rotor rotating at synchronous speed and no load torque. The purpose for this procedure is to measure the no-load losses such as core loss, friction loss, and windage loss of a synchronous generator. These losses occur because the alternator spins unnecessarily, reducing its efficiency and wasting energy. To create an appropriate torque, only a small amount of electricity is required.The magnetizing path impedance is high enough to block current passage. This means that only a small current is delivered to the machine. This causes the stator-impedance value to decrease and the rated voltage to be applied across the magnetizing branch. However, the decrease in stator-impedance value and power consumed due to stator resistance are negligible compared to the applied voltage.

Short-circuit test

The purpose of the short circuit test is to compute the synchronous reactance of the synchronous motor.All of the electricity will travel via the synchronous reactance since the motor is short-circuited. The voltage provided, E, is kept constant at 127V per phase, the synchronous reactance can be computed using the formula, Xs = E/Isx. The short circuit test can also be used to gather information about the capacity of the synchronous generator. The test is performed by short-circuiting the machine's terminals. The armature reaction of the machine prevents it from becoming saturated during testing. It would be possible to determine the value of the armature current, internal impedance and the synchronous reactance from measuring the short-circuited current [3].

Load test

The load test is carried out to examine the impact of the load on the stator voltage and to confirm the accuracy of the synchronous reactance derived from the no-load and short circuit tests.The load bank generator test will subject the generator to varying load conditions in order to assess how the generator handles the increased power demand [4].Depending on the loading conditions (resistive, inductive and capacitive), the armature reaction's impact may differ which will result in a shift from positive inductive loading to negative in capacitive loading. The direction of current flow is critical to

checked

the alternator under inductive or capacitive loads when the voltage is applied. In an inductive load, the current lags voltage by up to half a cycle.In a capacitive load, the current leads voltage. High-reactive loads require more current from the alternator than fully resistive loads. The load test is performed to determine how the stator voltage varies with the armature current under different loading conditions.

2. Discuss the change in voltage regulation of a synchronous generator when it is connected to different types of load (resistive, inductive, capacitive). [10 Marks]

The voltage regulation of the synchronous generator when it is connected to the resistive load

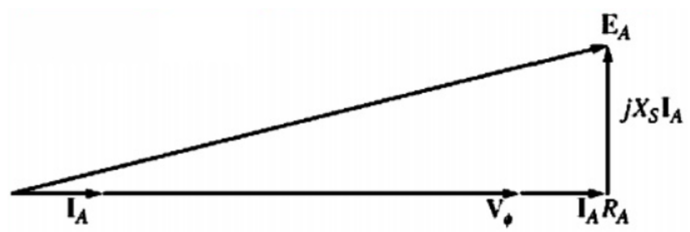

Fig 13: The phasor diagram of a synchronous generator at unity p.f (power factor) [6]

With a resistive load, the stator voltage drops as the armature current rises. As a result, the voltage regulation is on the positive side. Because the synchronous reactance creates a voltage drop, the voltage at resistive loads is reduced. When a resistive load is connected to a synchronous generator, it has a unity power factor which will result in an increase in the magnitude of induced current Ia. Since the power factor is 1, the current angle will be the same as the terminal voltage E.

The voltage regulation of the synchronous generator when it is connected to the inductive load

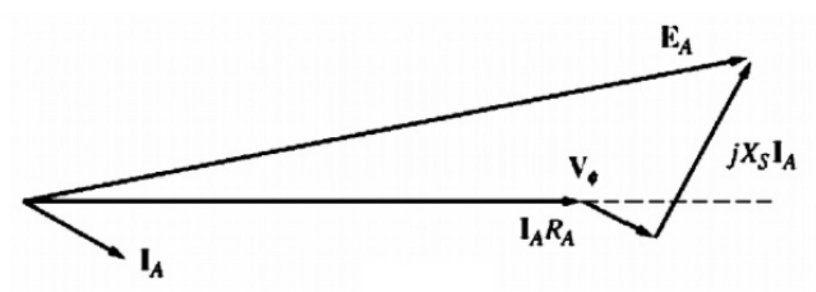

Fig 14: The phasor diagram of a synchronous generator at lagging p.f (power factor) [6]

When an inductive load is connected to a synchronous generator, the stator voltage decreases as the armature current increases. This results in a positive voltage regulation that grows faster than that of a resistive load as the armature current increases. Inductive loads produce a lagging current, which, as shown in the inductive load vector diagram, leads to a significant reduction in voltage magnitude *at the synchronous reactance. As a result, the voltage regulation of an inductive load is greater than that of a resistive load.*

The voltage regulation of the synchronous generator when it is connected to the capacitive load

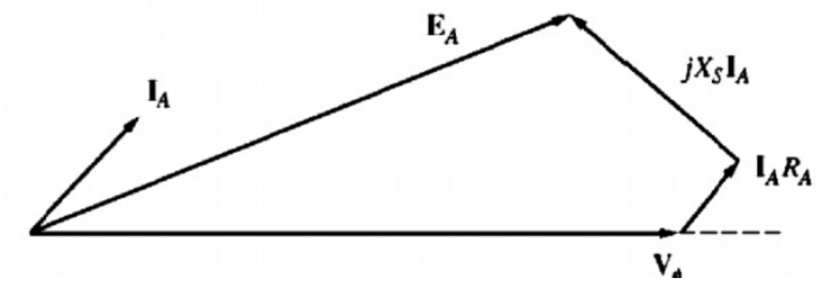

Fig 15: The phasor diagram of a synchronous generator at leading p.f (power factor) [6]

When a capacitive load is connected to a synchronous generator, the stator voltage increases as the armature current increases and negative voltage regulation is used. Capacitive loads provide reactive power to the line, resulting in a voltage that is higher than that of the generator. A capacitive load generates a leading current that is converted into a voltage gain by the synchronous reactance when viewed from the vector diagram's perspective, resulting in an increase in voltage.

Conclusion and Findings [14 Marks]

(Include your conclusion on the experiment done. State the learning outcomes of this experiment.)

Three experiments were performed in this lab which are the no-load test, the short-circuit test, and the load test. During the load test, three types of loads were utilized which are resistive, inductive, and capacitive loads. The experiments are carried out to measure the excitation current, armature current and the stator voltage characteristic of the three-phase synchronous generator.

<u>The no-load test</u>
In the no-load test, increasing the excitation current resulted in an increase in the induced stator voltage. The no-load test was carried out by varying the excitation current from approximately 0A to 0.9A with steps of approximately 0.05. As we can see from the graph, the no-load characteristic of the generator is linear until the excitation current reaches 0.85A, at which point the iron parts within the machine become saturated. The saturation of iron parts can cause non-linearity in the generator's behavior, which may explain the change in the no-load characteristic beyond an excitation current of 0.85A.

<u>The short-circuit test</u>
In the short-circuit test, an increase in the excitation current will result in a corresponding increase in the armature current. The short circuit test is conducted by increasing the excitation current from approximately 0A to 0.45A with steps of approximately 0.05. We can also conclude that the armature reaction prevents the machine from saturating when it is short circuited.

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The load test
Finally, during the load test, resistive and inductive loads were found to cause a decrease in the stator induced voltage as the armature current increased. In the case of the capacitive load, the stator induced voltage increased with an increase in the armature current.

References [6 Marks]

[1] T. Wildi, "Synchronous Generators," in Electrical Machines, Drives, and Power Systems, 6th ed., UK: Pearson, ch. 16, pp. 350.

[2] "Open Circuit Test and Short Circuit Test of Synchronous generator." Theengineeringknowledge.com. https://www.theengineeringknowledge.com/open-circuit-test-and-short-circuit-test-of-synchronous-generator/(accessed May 5, 2023).

[3] "What is Generator Load Bank Testing and How Is It Done?" loadbanksdirect.com. https://www.loadbanksdirect.com/about-lbd/blog/how-is-load-bank-generator-testing-done#:~:text=A%20load%20bank%20generator%20test,of%20testing%20the%20power%20 equipment.(accessed May 5, 2023).

[4] "Synchronous Generator Operating Alone." Thengineeringknowledge.com. https://www.theengineeringknowledge.com/synchronous-generator-operating-alone/(accessed May 5, 2023).

[5] Habib (2021) The load characteristics of alternator: Practical example, ICEEET. Available at: https://www.iceeet.com/load-characteristics-of-alternator/ (Accessed: 13 May 2023).

[6] Henry, "Phasor Diagram of a Synchronous Generator," The Engineering Knowledge, Oct. 06, 2019. https://www.theengineeringknowledge.com/phasor-diagram-of-a-synchronous-generator/

[7] "Phasor Diagram of Synchronous Generator or Alternator," Electrical Deck - All about Electrical & Electronics. https://www.electricaldeck.com/2021/01/phasor-diagram-of-synchronous-generator-or-alternator.html (accessed May 13, 2023).

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