BIRZEIT UNIVERSITY

Department of Electrical & Computer Engineering
ENEE2103 - Circuits and Electronics Laboratory

Experiment #5
Filters

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Abstract

In this experiment, we talk about filters, filter types: passive or active, filter order, cut-off frequency, 3db cut-off frequency, how to work practically with filters and the advantage of using an active filter, and the effect of frequency on the circuit. The tools required to carry out this experiment are DMM, oscilloscope, power-supply, function generator, an uA741 operation amplifier, resistors, capacitors, and an inductance decade box.

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1 Theory

Filters in circuits allow certain frequencies to pass through while blocking undesired frequencies. Filters are classified into two types: passive and active filters. Passive filters are made of passive components such as resistors, capacitors, and inductors. Active filters are made of active components such as transistors and op-amps. A filter order is the number of reactive components in the filter. Furthermore, filters have four basic types: low pass, high pass, band pass, and band stop.

1.1 Passive Filters

1.1.1 Low Pass Filter

As the name suggests, this type of filter allows low frequencies to pass through while blocking high frequencies.

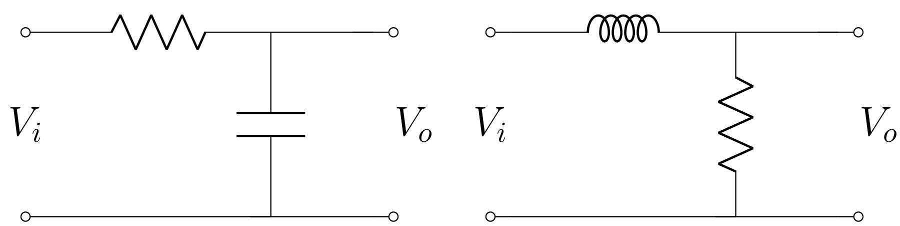


Figure 1: 1^{st} Order Passive Low-Pass filters

$$\begin{aligned} V_o &= \frac{X_c}{X_c + X_r} \times V_i \qquad & V_o &= \frac{X_r}{X_r + X_l} \times V_i \\ X_c &= \frac{1}{j\omega c} & X_l &= j\omega l \end{aligned} \tag{1}$$

The frequency is inversely proportional to the impedance X_c, and X_c is directly proportional to V_o, and by the same logic the frequency is directly proportional to X_l, and X_l is inversely proportional to V_o, which indicates that higher frequencies generate low V_o voltage (reject), and low frequencies generate high $V_o$ltage (pass).

The cut-off frequency is the frequency at which a point of inversion occurs, which indicates what high and low frequencies are, and it's given by:

$$f_c = \frac{1}{2\pi RC} \qquad or \qquad f_c = \frac{R}{2\pi L} \tag{2}$$

1.1.2 High Pass Filter

This type of filter is a complement of the low-pass filter since it rejects low frequencies and passes high ones.

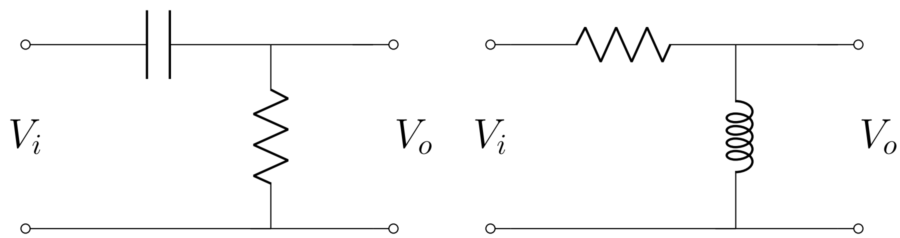


Figure 2: 1^{st} Order Passive High-Pass filters

$$\begin{aligned} V_o &= \frac{X_r}{X_c + X_r} \times V_i & \qquad V_o &= \frac{X_l}{X_r + X_l} \times V_i \\ X_c &= \frac{1}{j\omega c} & \qquad X_l &= j\omega l \end{aligned} \tag{3}$$

According to the above equations, the frequency is inversely proportional to the impedance X_c, X_c is inversely proportional to V_o, and by the same logic the frequency is directly proportional to X_l, and X_l is directly proportional to V_o, which indicates that higher frequencies generate high $V_o$ltage (pass), and low frequencies generate low V_o volltage (reject).

The cut-off frequency is the frequency at which a point of inversion occurs, which indicates what high and low frequencies are, and it's given by:

$$f_c = \frac{1}{2\pi RC} \qquad or \qquad f_c = \frac{R}{2\pi L} \tag{4}$$

1.1.3 Band Pass Filter

A band pass filter is a combination of a low pass and a high pass filter, which allows a certain band of frequencies to pass through while blocking the rest. It has two cut-off frequencies, f_{c1} and f_{c2}, which are the frequencies at which the filter starts to reject frequencies. The bandwidth is the difference between the two cut-off frequencies. It is a second-order filter, which means that it has two reactive components.

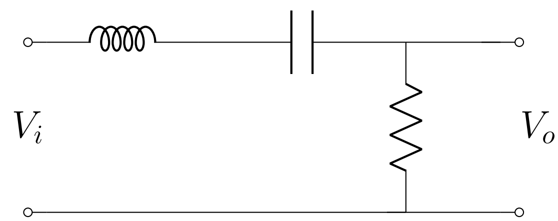


Figure 3: 2^{nd} Order Passive Band-Pass filters

The center frequency and the cut-off frequencies are given by:

$$f_0 = \frac{1}{2\Pi\sqrt{LC}} \tag{5}$$

$$f_{c1} = \frac{-\frac{R}{2L} + \sqrt{\frac{R}{2L}^2 + \frac{1}{LC}}}{2\Pi} \tag{6}$$

$$f_{c2} = \frac{\frac{R}{2L} + \sqrt{\frac{R}{2L}^2 + \frac{1}{LC}}}{2\Pi} \tag{7}$$

1.2 Active Filters

Passive RC filters such as low pass, high pass, and band pass filters use resistors and capacitors to filter electronic signals. However, the output signal is less than the input signal, which means that the signal gain is never greater than unity and load impedance affects the filter characteristics. Multi-stage passive filters can cause severe attenuation of the output signal. To control the loss of signal, active filters use active components such as transistors, FETs (Field Effect Transistors), and operational amplifiers in their design. These filters draw external power from the source to boost the output signal. [1]

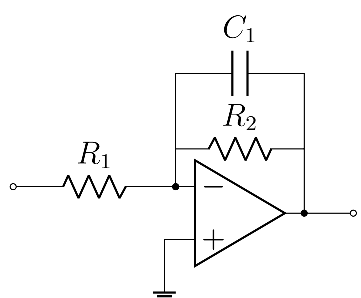


Figure 4: Active Low-Pass Filter

2 Procedure and Data Analysis

2.1 Passive Filters

2.1.1 First Order Filter

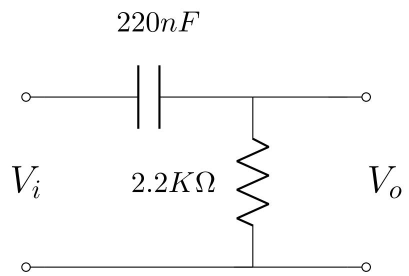


Figure 5: 1'st Order RC High-pass filter

The circuit above was connected, with a source V_i that has 1V RMS Value, and a frequency of 20Hz. The cut-off frequency was found by setting the frequency that satisfies

$$V_c = 0.706 \times V_{max} \tag{8}$$

and it was found to be 318Hz it was also found that the phase shift between the input and output signal to be 44.7 °, as shown in the following figure:

Figure 6: Cut-off frequency and phase shift

Frequency (Hz)	Vin (Vrms)	Vc (Vrms)	Phase	Log(f)	20Log(Vc/Vin)
20	1	1.09	-87.3	1.301029996	0.7485299588
31.8	1	1.08	-92.3	1.50242712	0.6684751097
159	1	0.974	-64	2.201397124	-0.2288208624
318	1	0.774	-45	2.50242712	-2.225180786
636	1	0.487	-26.9	2.803457116	-6.249420776
1272	1	0.265	-12.8	3.104487111	-11.53508252
2544	1	0.135	-6.45	3.405517107	-17.39332463
3180	1	0.109	-3.43	3.50242712	-19.25147004
3816	1	0.091	-3.01	3.581608366	-20.81917215
4452	1	0.074	-1.93	3.648555156	-22.61536561
5088	1	0.07	-1.83	3.706547103	-23.0980392
6360	1	0.058	-0.237	3.803457116	-24.73144013

Table 1: Low-pass filter data points

From the table above, $20\log\frac{Vc}{Vin}$ was plotted against $log f$ using google sheets, from the plot we saw that it was a low-pass filter which indicated that the load on R is a high-pass filter, having the $-3dB$ point cross the x-axis at $\log f = 2.65$ hence, the 3dB cut-off frequency $f_{3dB} = 10^{2.75} = 562.34Hz$ which is not an accurate read and it goes back because there is no enough data point to the plot or an error rate in the DMM.

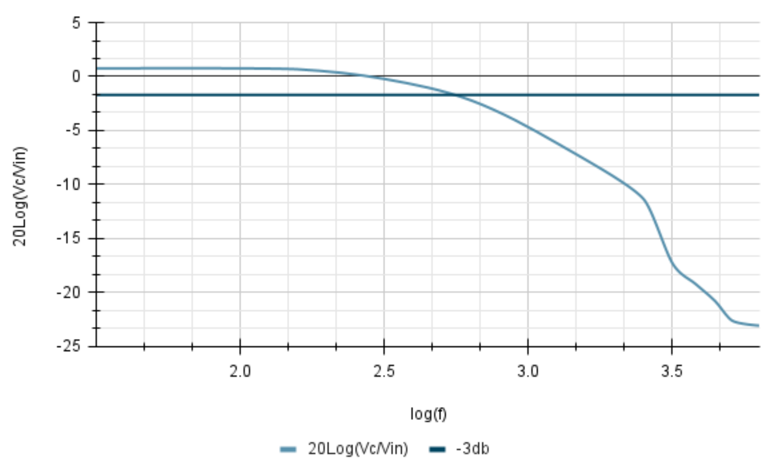


Figure 7: $20\log\frac{Vc}{Vin}$ vs $log f$

2.1.2 Second Order Filter

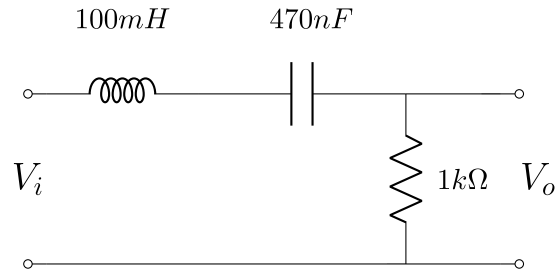


Figure 8: 2^{nd} Order RLC Band-Pass filters

The above circuit was connected to a 2V RMS power source with a frequency equal to the resonance frequency. theoretically, it's given by:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = 734.13Hz \tag{9}$$

and we got it experimentally by changing the frequency until the phase shift between V_i and V_o is equal to zero, which occurs at $f = 676.27Hz$ as shown in the following figure:

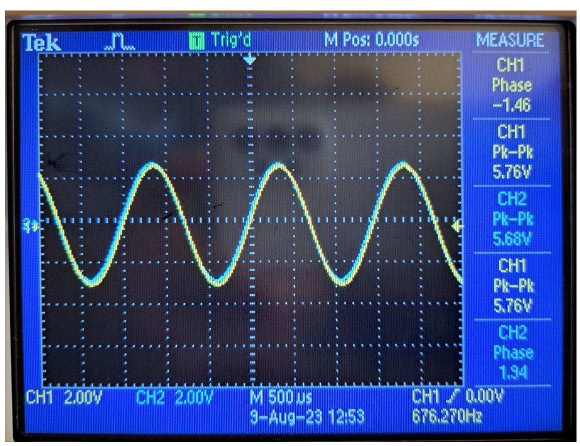


Figure 9: Resonance[Center] Frequency of the band-pass filter

The method we used to find the cut-off frequency is by using the fact that at cut-off frequencies the maximum voltage drops to 0.707 of its value, hence it occurs at $Vc + Vl = 0.707 * 1.09 = 0.7707$ 2 times, one before the resonance frequency and the another after the resonance frequency as shown in the figure below:

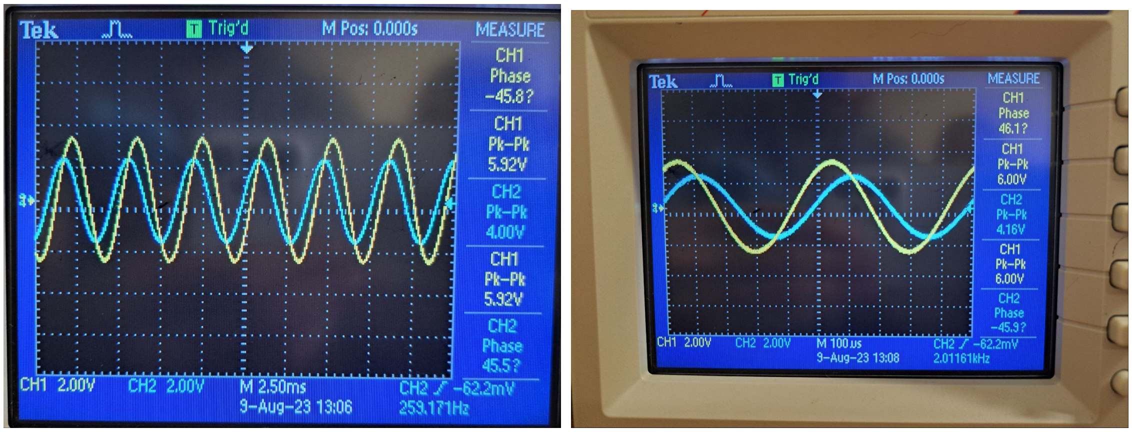


Figure 10: Band-pass filter cut-off frequencies

as shown above the two cut-off frequencies are 259.17Hz and 2016Hz.

Frequency	Vin(Vrms)	Vr(Vrms)	(Vc+Vl) (Vrms)	log f	20Log((Vc+Vl)/Vin)	20Log(Vr/Vin)
26	2	0.17	2.06	1.414973348	0.2567444941	-21.41162149
78	2	0.5	2	1.892094603	0	-12.04119983
130	2	0.8	1.88	2.113943352	-0.537442928	-7.958800173
260	2	1.37	1.456	2.414973348	-2.757372414	-3.28618857
780	2	1.45	0.14	2.892094603	-23.0980392	-2.793239869
1300	2	1.73	0.96	3.113943352	-6.375175252	-1.259677851
1820	2	1.46	1.38	3.260071388	-3.223018185	-2.733542798
338	2	1.6	1.16	2.5289167	-4.731440129	-1.93820026
676	2	1.93	0.107	2.829946696	-25.43292436	-0.3094537331
1352	2	1.7	1.02	3.130976692	-5.848596478	-1.411621486
2704	2	1.1	1.71	3.432006687	-1.360677705	-5.19274621
2000	2	1.37	1.481	3.301029996	-2.609498743	-3.28618857
4000	2	0.77	1.9	3.602059991	-0.4455278942	-8.29078541
8000	2	0.377	2.05	3.903089987	0.2144773078	-14.49377291
20000	2	0.033	2.07	4.301029996	0.2988069959	-35.65032112
24000	2	0.003	2.06	4.380211242	0.2567444941	-56.47817482
28000	2	0.035	2.05	4.447158031	0.2144773078	-35.13923903
32000	2	0.066	2.04	4.505149978	0.1720034352	-29.6297212
40000	2	0.128	2.01	4.602059991	0.04332123513	-23.87640052

Table 2: Band-pass filter data points

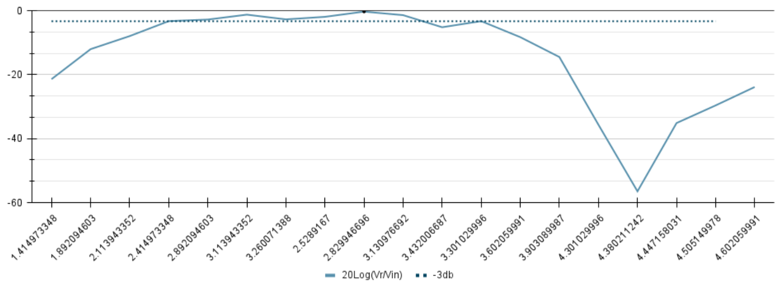


Figure 11: $20 \log \frac{V_r}{V_i}$ vs $\log f$

The $20 \log \frac{V_r}{V_in}$ was plotted vs $log\ f$, from the plot, we concluded that it is a band-pass filter with the 3db value crossing 2-values, 2.4 and 3.28, and in frequency, they are represented as $f_{c1} = 251.18Hz,\ f_{c2} = 1905.1Hz$ which are accepted values considering the theoretical and practical values.

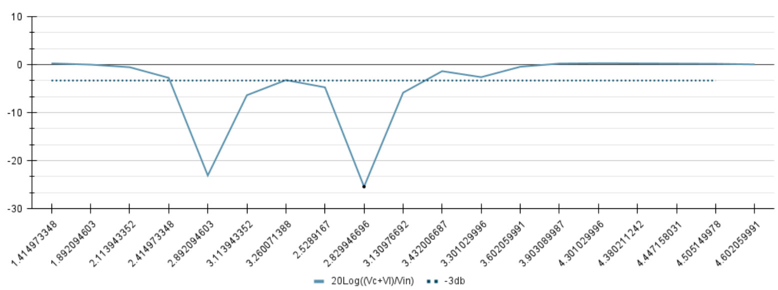


Figure 12: $20 \log \frac{V_c+V_L}{V_i}$ vs $\log f$

We noticed, from the above graph, that $V_c + V_l$ has the same cut-off frequency as V_r that we discussed earlier, and we notice that it is a band-reject filter but it has some error in the data so the values are caved in instated of going down as it should in the middle.

2.2 Active Filters

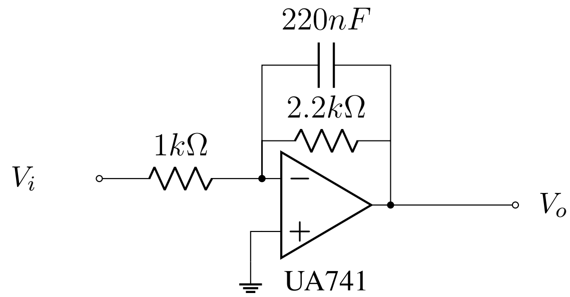


Figure 13: Active Low-Pass Filter

The circuit above was connected to V_i with 2 Vrms amplitude and a cut-off frequency of f_c. We obtained f_c using the same method used in (Figure 7) and we found it to have the value of 325.9 as shown in the following figure:

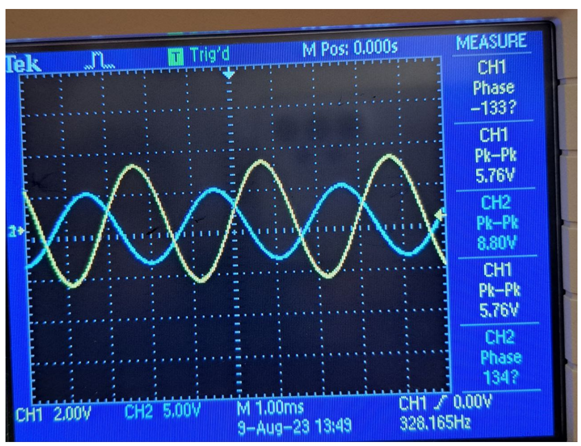


Figure 14: Cut-off Frequency of the Active Low-pass filter

Frequency	Vin (Vrms)	Vd (Vrms)	log f	20 log (Vd/Vin)
32.84	2	4.24	1.516403148	6.526717219
65.68	2	4.18	1.817433144	6.402925722
131.36	2	3.95	2.11846314	5.911341999
262.72	2	3.31	2.419493135	4.375959962
328.4	2	3	2.516403148	3.521825181
492.6	2	2.32	2.692494408	1.289159785
656.8	2	1.9	2.817433144	-0.4455278942
1313.6	2	1.02	3.11846314	-5.848596478
1970.4	2	0.69	3.294554399	-9.243618099
3284	2	0.42	3.516403148	-13.55561411
3940.8	2	0.35	3.595584394	-15.13923903
6568	2	0.21	3.817433144	-19.57621402

Table 3: High-pass filter data points

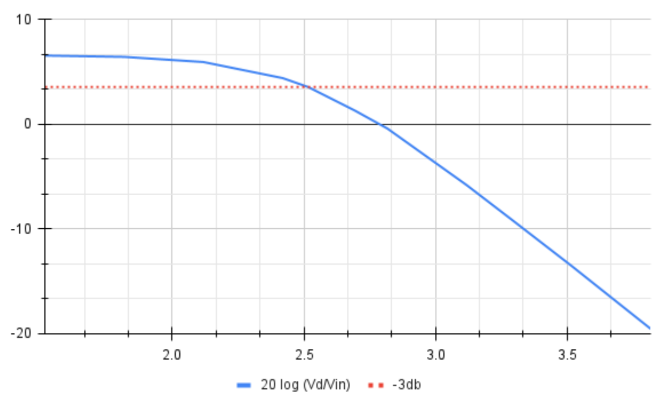


Figure 15: $20\log(Vd/Vi)$ over $log\ f$

From the above graph, we noticed that the low-pass filter has a cut-off frequency of $316.23Hz$ which is an acceptable result since the theoretical value is $f_c = \frac{1}{2\pi RC} = 328.83Hz$.

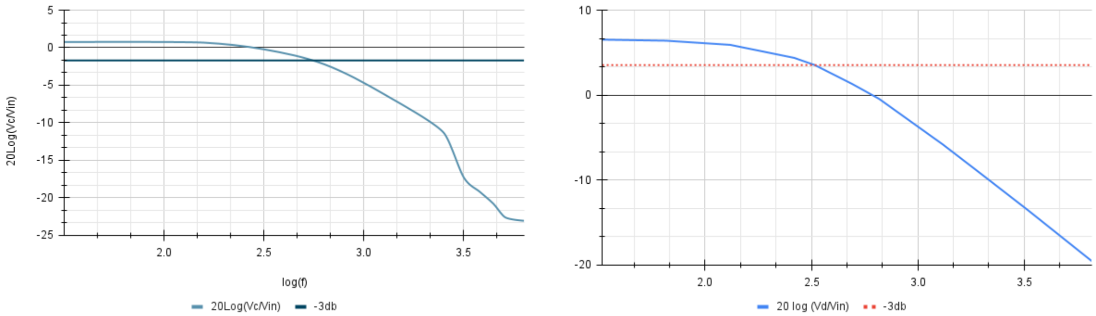


Figure 16: Passive vs Active Low-pass filter

In comparison with the low-pass filter that we discussed (Figure: 7) we notice that the active filter is working as an amplifier with a maximum gain of $\approx 7dB$ while the passive filter is losing the amplitude with a gain under zero.

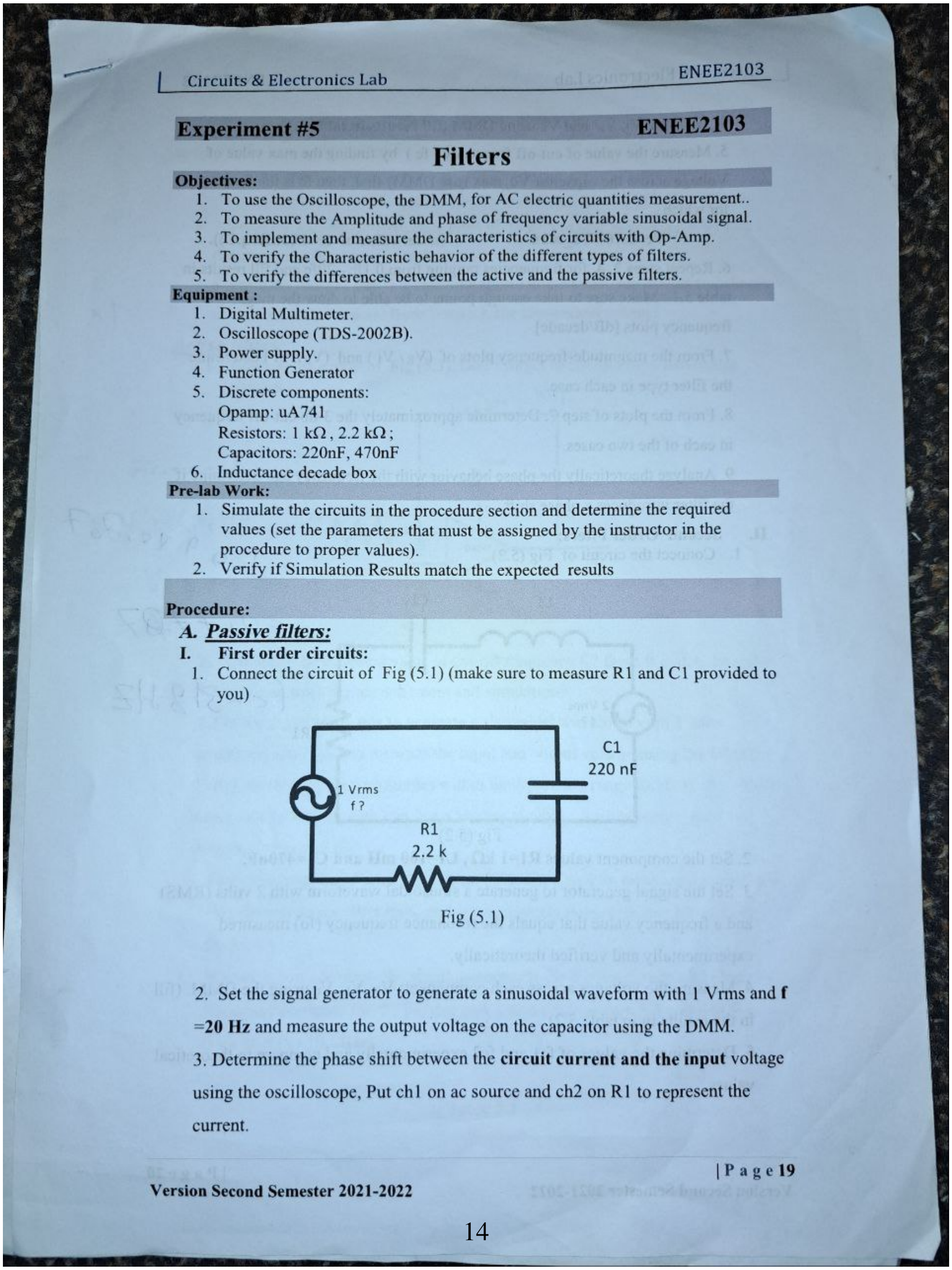
3 Conclusion

In conclusion, active filters are more efficient and have a higher gain than passive filters, filters work by attenuating the amplitude relative to unwanted frequency, and how the filter elements affect the input-to-output phase.

References

[1] ElectronicsHub. Active filters design. https://www.electronicshub.org/active-filters-design/

Appendix



Circuits & Electronics Lab ENEE2103

Experiment #5 **ENEE2103**

Filters

Objectives:

1. To use the Oscilloscope, the DMM, for AC electric quantities measurement..
2. To measure the Amplitude and phase of frequency variable sinusoidal signal.
3. To implement and measure the characteristics of circuits with Op-Amp.
4. To verify the Characteristic behavior of the different types of filters.
5. To verify the differences between the active and the passive filters.

Equipment :

1. Digital Multimeter.
2. Oscilloscope (TDS-2002B).
3. Power supply.
4. Function Generator
5. Discrete components:
   Opamp: uA741
   Resistors: 1 kΩ , 2.2 kΩ ;
   Capacitors: 220nF, 470nF
6. Inductance decade box

Pre-lab Work:

1. Simulate the circuits in the procedure section and determine the required values (set the parameters that must be assigned by the instructor in the procedure to proper values).
2. Verify if Simulation Results match the expected results

Procedure:

A. *Passive filters:*

I. First order circuits:

1. Connect the circuit of Fig (5.1) (make sure to measure R1 and C1 provided to you)

Fig (5.1)

2. Set the signal generator to generate a sinusoidal waveform with 1 Vrms and **f =20 Hz** and measure the output voltage on the capacitor using the DMM.
3. Determine the phase shift between the **circuit current and the input** voltage using the oscilloscope, Put ch1 on ac source and ch2 on R1 to represent the current.

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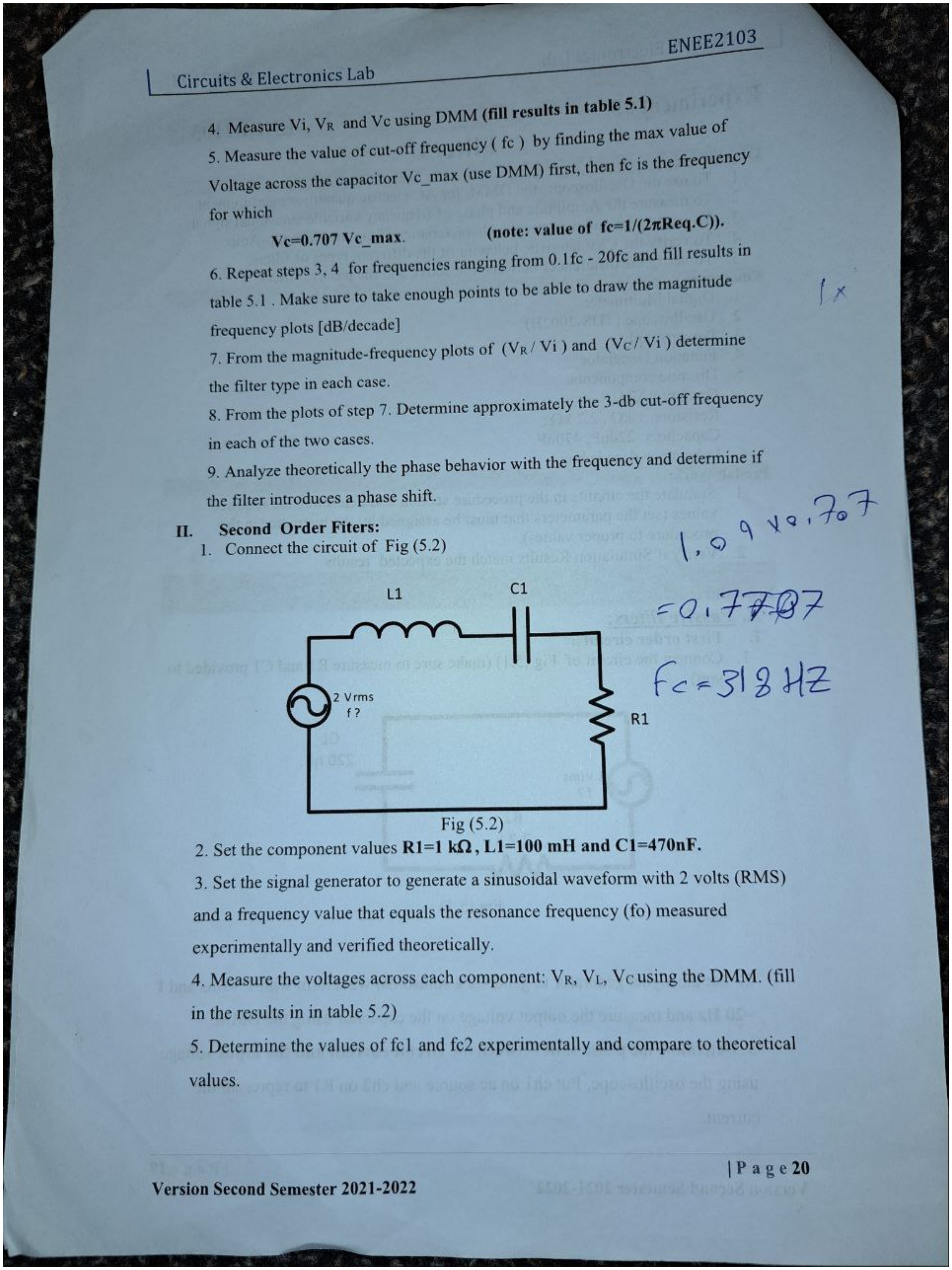
Figure 17: Page 1



4. Measure Vi, V_R and Vc using DMM **(fill results in table 5.1)**
5. Measure the value of cut-off frequency (fc) by finding the max value of Voltage across the capacitor Vc_max (use DMM) first, then fc is the frequency for which

Vc=0.707 Vc_max. **(note: value of fc=1/(2πReq.C)).**

6. Repeat steps 3, 4 for frequencies ranging from 0.1fc - 20fc and fill results in table 5.1 . Make sure to take enough points to be able to draw the magnitude frequency plots [dB/decade]
7. From the magnitude-frequency plots of (V_R/ Vi) and (V_C/ Vi) determine the filter type in each case.
8. From the plots of step 7. Determine approximately the 3-db cut-off frequency in each of the two cases.
9. Analyze theoretically the phase behavior with the frequency and determine if the filter introduces a phase shift.

1x

1,09 x 0.707

=0.7707

Fc=318 HZ

II. Second Order Fiters:

1. Connect the circuit of Fig (5.2)

Fig (5.2)

2. Set the component values **R1=1 kΩ, L1=100 mH and C1=470nF.**
3. Set the signal generator to generate a sinusoidal waveform with 2 volts (RMS) and a frequency value that equals the resonance frequency (fo) measured experimentally and verified theoretically.
4. Measure the voltages across each component: V_R, V_L, V_C using the DMM. (fill in the results in in table 5.2)
5. Determine the values of fc1 and fc2 experimentally and compare to theoretical values.

Figure 18: Page 2

6. Repeat step 4 for frequencies ranging from 0.1fc1 - 20fc2, take enough points to be able to draw the magnitude frequency plot [dB/decade] as in table 5.2

7. From the magnitude-frequency plots of (V_R / V_i) and $((V_C + V_L)/ V_i)$ determine the filter type in each case.

8. From the plots of step 6. Determine approximately the 3db cut-off frequency in each of the two cases. **Does it match the theoretical values?**

Active filters:

1. Connect the circuit of Fig (5.3). Don't forget to connect the bias voltage sources

Req

$Fc = \frac{1}{2\pi R_{eq} C}$

$Fc = 328.9$ HZ

V_{p-p} , 5.76

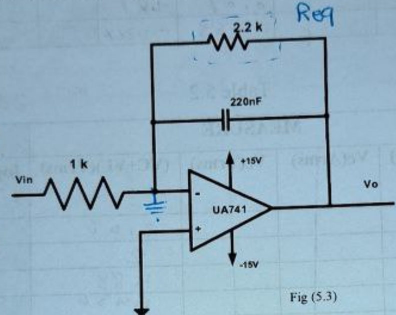


Fig (5.3)

2. Calculate the expected value of cut-off frequency f_c? Does it match the value obtained from the measurement and simulation?

4. Set the signal generator to generate a sinusoidal waveform with 3 volts amplitude and $f = f_c$ and measure the input and output voltage using the DMM.

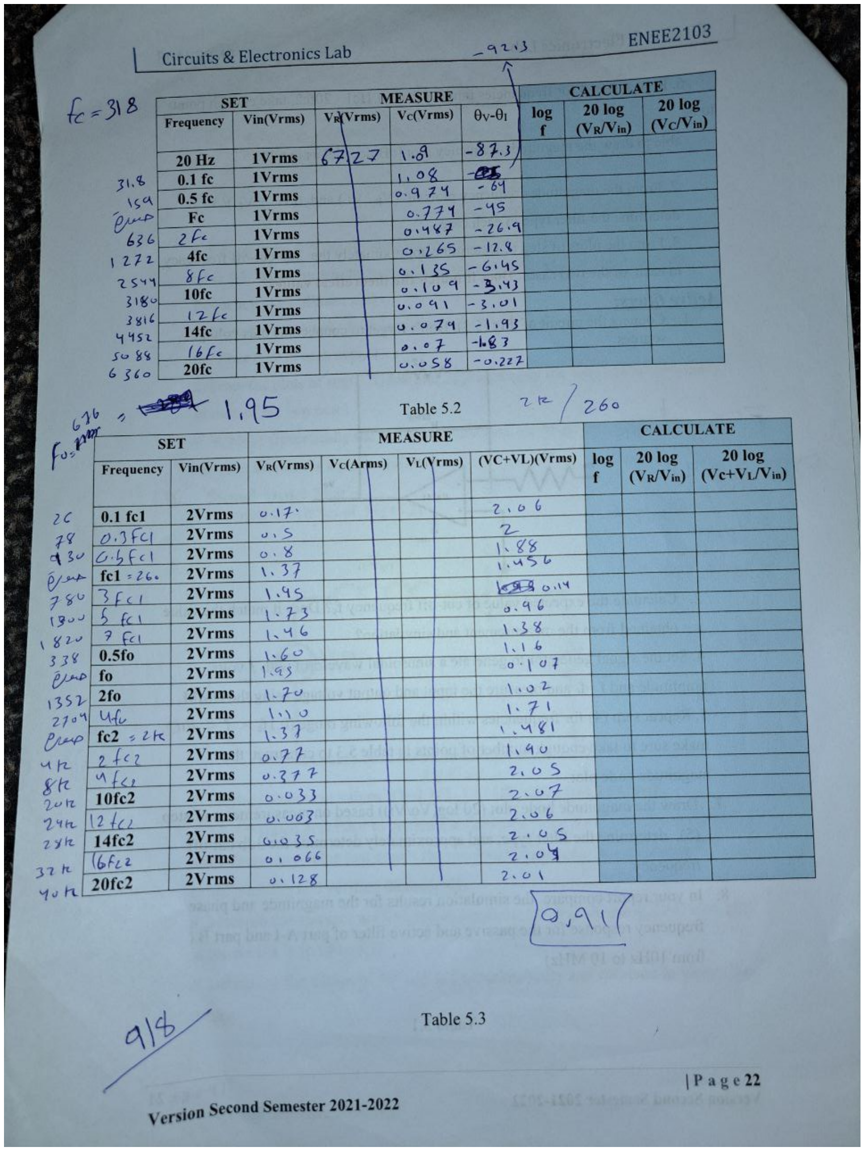
5. Repeat step (4) for frequencies within the following range ($0.1f_c < f < 40f_c$), make sure to take enough number of points in table 5.3 to construct the magnitude bode plot.

7. Draw the magnitude bode plot (20 log(Vo/Vi)) based on measurements of step (5), determine the filter type, and approximately determine the 3db cut-off frequency.

8. In your report compare the simulation results for the magnitude and phase frequency response for the passive and active filter of part A-I and part B (from 10Hz to 10 MHz)

Table 5.1

Figure 19: Page 3



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fc = 318

	SET		MEASURE			CALCULATE		
	Frequency	Vin(Vrms)	V_R(Vrms)	V_C(Vrms)	$\theta_V-\theta_I$	log f	20 log (V_R/V_{in})	20 log (V_C/V_{in})
	20 Hz	1Vrms	67.27	1.09	-87.3			
31.8	0.1 fc	1Vrms		1.08	[illegible]			
159	0.5 fc	1Vrms		0.974	-64			
Ɵ/ex	Fc	1Vrms		0.774	-45			
636	2fc	1Vrms		0.487	-26.9			
1272	4fc	1Vrms		0.265	-12.8			
2544	8fc	1Vrms		0.135	-6.45			
3180	10fc	1Vrms		0.109	-3.43			
3816	12fc	1Vrms		0.091	-3.01			
4452	14fc	1Vrms		0.079	-1.93			
5088	16fc	1Vrms		0.07	-1.83			
6360	20fc	1Vrms		0.058	-0.227			

Fo = 676 = 1.95

Table 5.2

2k / 260

	SET		MEASURE				CALCULATE		
	Frequency	Vin(Vrms)	V_R(Vrms)	V_C(Arms)	V_L(Vrms)	(VC+VL)(Vrms)	log f	20 log (V_R/V_{in})	20 log (V_C+V_L/V_{in})
26	0.1 fc1	2Vrms	0.17			2.06			
78	0.3 fc1	2Vrms	0.5			2			
130	0.5 fc1	2Vrms	0.8			1.88			
Ɵ/ex	fc1 = 260	2Vrms	1.37			1.456			
780	3 fc1	2Vrms	1.95			0.14			
1300	5 fc1	2Vrms	1.73			0.96			
1820	7 fc1	2Vrms	1.46			1.38			
338	0.5fo	2Vrms	1.60			1.16			
Ɵ/ex	fo	2Vrms	1.93			0.107			
1352	2fo	2Vrms	1.70			1.02			
2704	4fo	2Vrms	1.10			1.71			
Ɵ/ex	fc2 = 2k	2Vrms	1.37			1.481			
4k	2 fc2	2Vrms	0.77			1.90			
8k	4 fc2	2Vrms	0.377			2.05			
20k	10fc2	2Vrms	0.033			2.07			
24k	12 fc2	2Vrms	0.003			2.06			
28k	14fc2	2Vrms	0.035			2.05			
32k	16fc2	2Vrms	0.066			2.04			
40k	20fc2	2Vrms	0.128			2.01			

$\boxed{0.91}$

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Table 5.3

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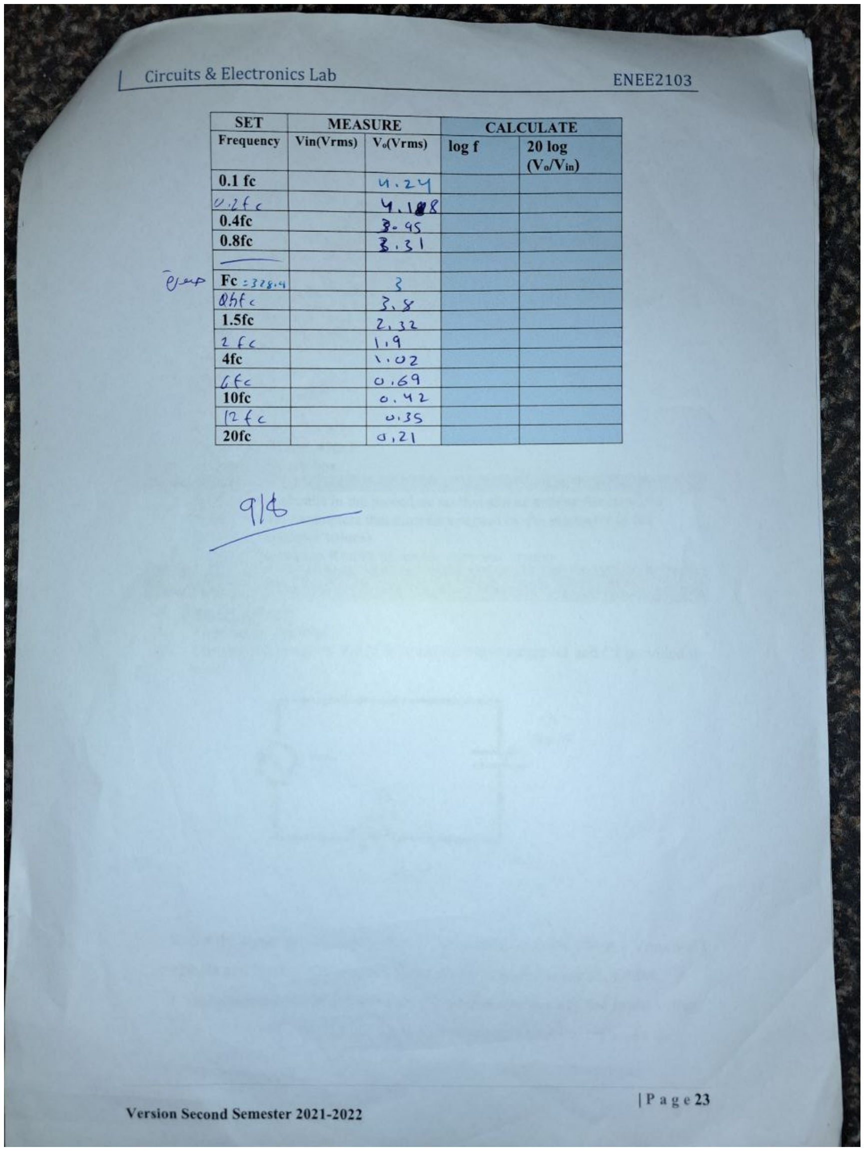
Figure 20: Appendix - Page 4


Circuits & Electronics Lab ENEE2103

SET	MEASURE		CALCULATE	
Frequency	Vin(Vrms)	V_o(Vrms)	log f	20 log (V_o/V_{in})
0.1 fc		4.24		
0.2fc		4.18		
0.4fc		3.95		
0.8fc		3.31		
Fc = 318.4		3		
0.6fc		3.8		
1.5fc		2.32		
2 fc		1.9		
4fc		1.02		
6fc		0.69		
10fc		0.42		
12 fc		0.35		
20fc		0.21		

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Figure 21: Appendix - Appendix - Page 5