

1809797

by Lourens Brits

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TIME SUBMITTED	19-MAY-2020 10:31AM (UTC+0100)	WORD COUNT	3604
SUBMISSION ID	128227704	CHARACTER COUNT	22044



Course : HNC Electrical and Electronic Engineering

Module : SGEE5000 – Electronics 2

Assignment : 2 – Active Filter design

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Date Submitted : 19/05/2020

Word Count : 2552

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1. Introduction, Aims and Objectives

Research will be carried out on active filters, in particular, Bessel, Tschebyscheff and Butterworth. These filters' characteristics, uses and integration into control systems will be investigated, compared and contrasted. By conducting comprehensive research these objectives will be met, enabling the various low and high pass filters to be designed, tested and evaluated, by means of calculating desired outcomes, simulating findings and conducting thorough testing of the filters.

Once research has been conducted, three 5th order low pass filters will be designed, using the three aforementioned filter types.

On completion of the 5th order low pass filters, three high pass Butterworth filters will be designed of the following orders, 3rd, 6th and 9th order.

Write an executive summary rather than aims and objectives.

2. Research

Filter Background

Filters are networks designed to pass signal frequencies in certain bands, known as pass bands, whilst blocking or attenuating other frequencies that are found in the stop or attenuation bands. (Bird, 2010)

The pass band of filter requires the attenuation to ideally be zero, thus enabling the required frequencies to pass, whereas in the attenuation band, the attenuation should ideally be infinite, creating what's known as the cut-off frequency. (Bird, 2010)

The cut-off frequency is the frequency where the attenuation changes to enable the filter to pass the desired frequencies, and is calculated with the equation $f_c = \frac{1}{2\pi RC}$. (Aspencore, 2020)

Filters are classified, as active or passive, where active filters contain one or more power sources and passive filters contain no power source. (Bird, 2010)

Depending on the desired effect of the filter (high or low-pass), different resistor – capacitor configurations can be used. For filters required to pass low frequencies (low pass filter), the resistor, op-amp, capacitor configuration will be as shown in figure 1, using series inductors and shunt capacitors. Whereas the high pass filter configuration is shown in figure 2, using series capacitors and shunt inductors. (Bird, 2010)

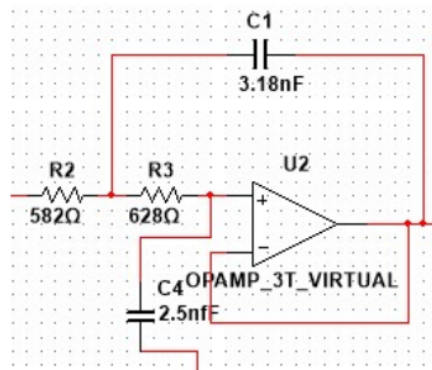


Figure 1 - Low pass filter

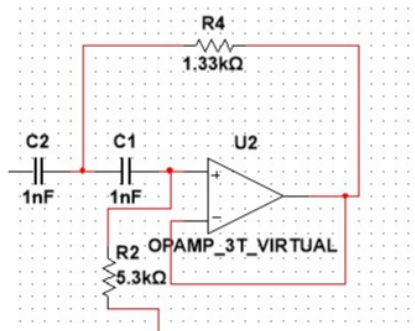


Figure 2 - High pass filter

Include researched versions of the circuit here rather than your practicals.

The Sallen-Key topology is used to design cascading filters. This topology is used as the building blocks to design and build high and low-pass cascading filters. This topology uses one non-inverting op-amp as well as two resistors to create a voltage-controlled voltage source, with high input impedance and low output impedance as well as stability. These characteristics enables the filters to be used in a cascaded manner to achieve high order filters. (Aspencore, 2020)

The three filters that will be researched area, Bessel, Butterworth and Tschebyscheff.

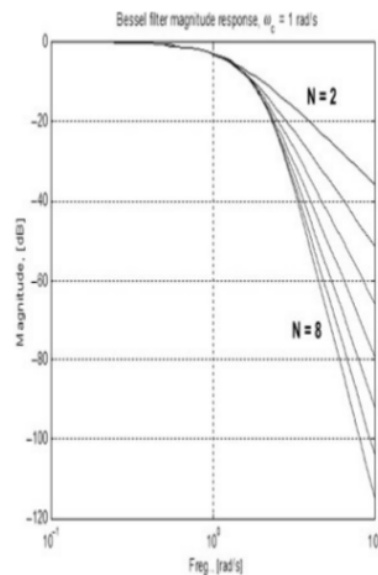
Bessel.

The Bessel filter is most commonly used in RF and analogue video signal processing, this is due to the fact that it preserves the output wave shape, as well as exhibiting a linear phase response. This is particularly important with RF applications. (Electronicsnotes, 2020)

The Bessel filter response is less sharp that of the Butterworth, and exhibits a more gradual roll-off with very little over-shoot. (Thompson, 2014)

Transition from pass-band to stop band is slower than other filters as well as shallower. (Electronicsnotes, 2020)

Figure 3 shows the magnitude response for 2nd through to 8th order, from this it is clear to see that the roll-off is fairly gradual in the pass-band and cut-off band. (Thompson, 2014)



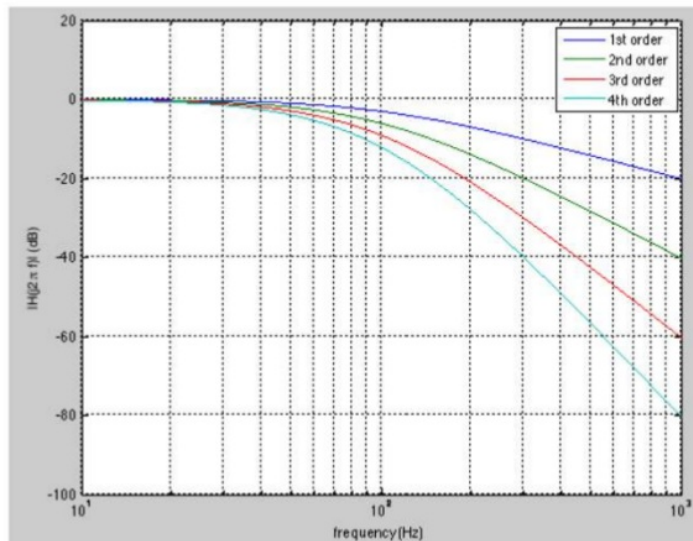
(Thompson, 2014)

Figure 3 - Bessel filter magnitude response

Butterworth

Butterworth filters are commonly used for audio processing or control applications, as it exhibits a very flat response in the pass-band. As well as the flat response Butterworth filters have the sharpest possible roll-off, without introducing peaking. (Thompson, 2014)

It is clear to see from figure 4 that the response of the Butterworth filter is very flat compared to that of the Bessel.



(Wang, 2019)

Figure 4 - Butterworth filter magnitude response

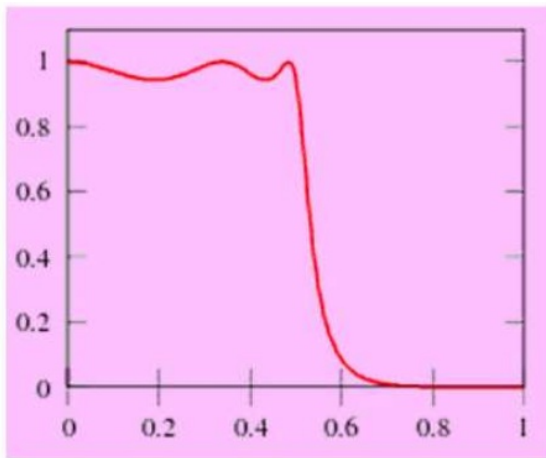
These filters pass signals without introducing any distortions in the pass-band. The rate of roll-off is determined by the number of inductors and capacitors, as they will determine the number of poles in the circuit. Butterworth filter poles lie in a circle in the complex plane. (Electronicshub, 2020)

Tschebyescheff

These filters allow for very fast roll-off, through allowing a ripple to occur in the frequency response. These ripples are called pass-band ripples, the roll-off becomes steeper as the ripple increases. There is a trade off between ripple and roll-off. If the ripple is set to 0% this will be a Butterworth filter. Tschebyescheff filters separate frequency bands from one-another. (Smith, 1997)

There are two types of Tschebyescheff filters, type 1 and type 2. The type 1 filter allows the ripple to only be in the pass-band, whereas the type 2 have the ripple only in the stop band. (Smith, 1997)

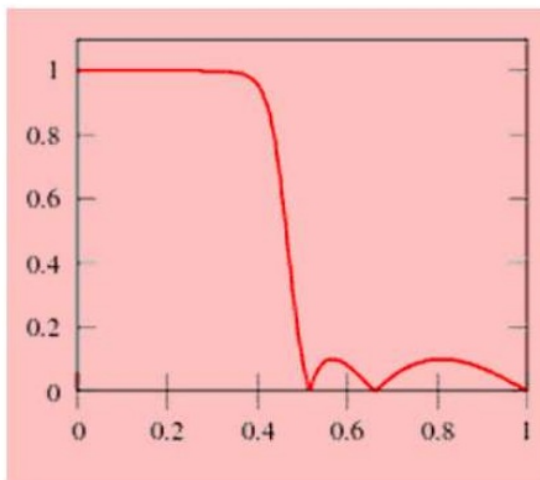
Figure 5 shows the ripple in the pass band before the fast roll-off occurs.



(ELPROCUS, 2020)

Figure 5 - Tschebyescheff filter pass-band ripple and roll-off

Figure 6 shows the stop-band ripple, or equiripple occurring. (ELPROCUS, 2020)



(ELPROCUS, 2020)

Figure 6 - Type 2 Tschebyescheff filter stop-band response

Filter comparison table

	Bessel	Butterworth	Tschebyescheff
Pass Band	flat	very flat	Type 1 - Rippled, Type 2 - flat
Roll-off	very gradual	slower than Tschebyescheff	Steep
Ripple	none	none	type 1 - pass band, type 2 - dead band
Phase shift	none	Increases with increase in order	Poor
Use	RF	Control applications + many more	RF filters
Overshoot	Small amount	considerable - increases with order increase	some

Figure 7 shows the magnitude responses of the 5th order filters on the same bode plot.

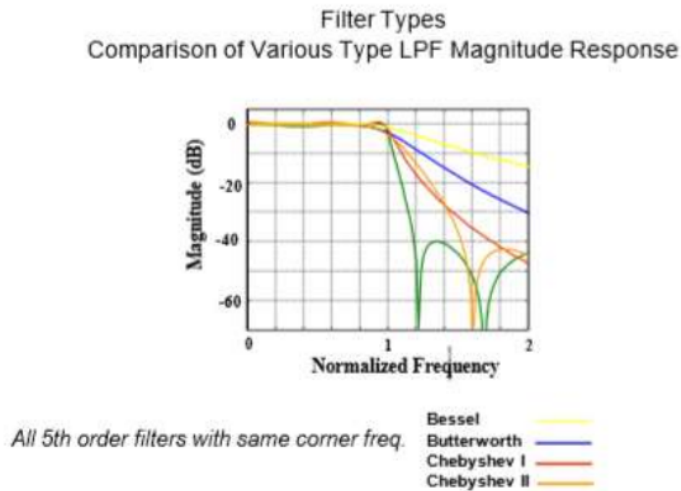


Figure 7 - Bessel, Butterworth and Tschebyescheff response

(ELPROCUS, 2020)

From the research conducted the following comparisons and contrasts can be made;

The Bessel filter has very gradual roll-off, in contrast with the Butterworth, which is very steep, but not as steep as the Tschebyescheff. Pass band of the Bessel is fairly flat, but not as flat as the Butterworth, whereas the Tschebyescheff_type 1 exhibits a ripple.

Bessel is best suited for applications where the output signal has to match the input signal, such as RF. Butterworth filters are used in high quality filtering is needed, such as data converters or high-quality audio applications, amongst others due to its maximally flat pass band. (Electronicshub, 2020)

Filter uses in modern electronic systems

Filters are used in control systems to reduce or manipulate the noise that is inherent in the signal. Noise in a closed loop control system is not ideal, for instance noise in a process control valve will cause erratic operation of the valve, which can lead to process issues and premature wear of parts.

Figure 8 shows the signal, signal noise and filtered signals. Yf1 and Yf2 are the filtered values, where Yf2 is heavily filtered. (Darby, 2019)

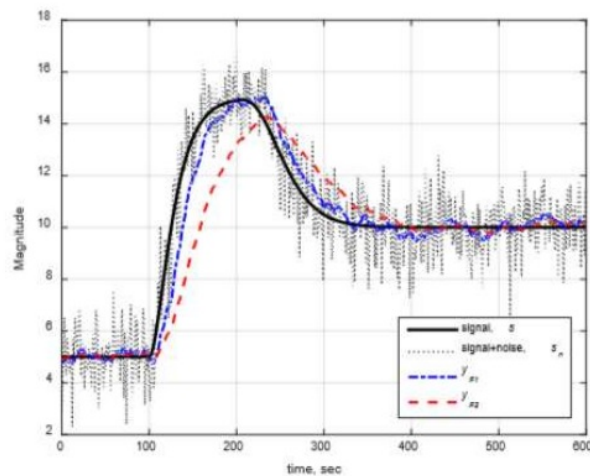


Figure 8 - Signal showing noise and filtered signal

The use of a filter in a closed loop flow control circuit is illustrated in figure 9. Here the circuit is tuned by the PID controller, with the controller output noise, as well as other inherent noise is filtered and fed back into the controller as filtered feedback. The filtering in conjunction with control loop tuning will reduce erratic flow control valve operation. There is a down side to filtering, this is in the form of lag, if the feedback loop is heavily filtered the controller will start to perform sluggish. (Darby, 2019)

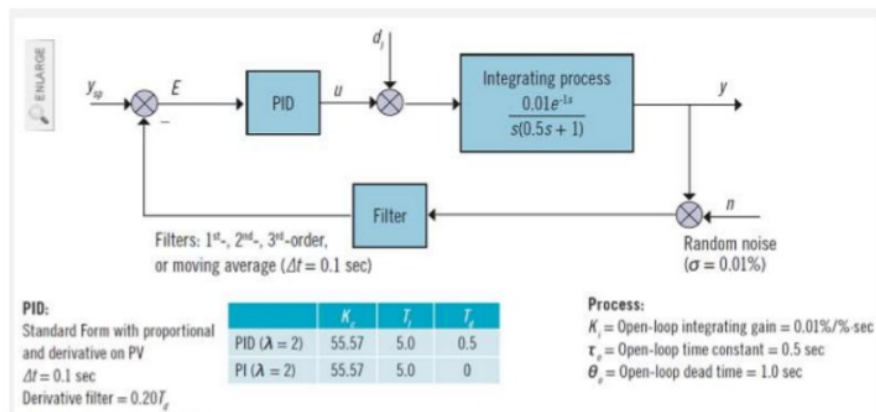


Figure 9 - Control loop with filtered feedback

(Darby, 2019)

Another application for filters, is to apply the filters at various stages of the control circuit depending on application. Figure 10 shows the control loop, as part of an advanced process control circuit (APC), here lag time has to be kept to a minimum, as there should be no delay in alarms activating for instance. Here the signal is filtered by an anti-aliasing filter, (as depicted by the Nyquist sampling theorem – where the maximum frequency of the input signal should be less than or equal to half of the sampling rate). (Instruments, 2019)

The signal is then converted to a digital signal before passing through the embedded filter and splitting to the PID loop and the communications gateway. This is don't to ensure the appropriate amount of filtering is applied, whilst keeping the lag time at an acceptable level. (Darby, 2019)

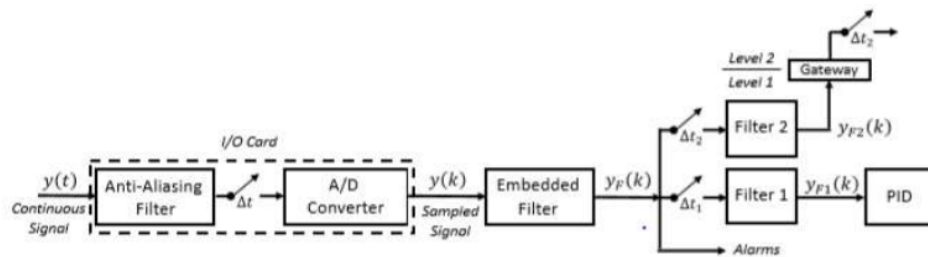


Figure 10 - APC filtered control loop

3. Design method, choices and calculations

The three-5th order low pass filters, Bessel, Butterworths and Tschebyscheff will be designed, simulated and critically analysed.

Bessel

The Bessel filter will be created, by utilising the published Bessel coefficients below in figure 11

Table 16-4. Bessel Coefficients

n	i	a _i	b _i	k _i = f _{ci} / f _c	Q _i
1	1	1.0000	0.0000	1.000	—
2	1	1.3617	0.6180	1.000	0.58
3	1	0.7560	0.0000	1.323	—
	2	0.9996	0.4772	1.414	0.69
4	1	1.3397	0.4889	0.978	0.52
	2	0.7743	0.3890	1.797	0.81
5	1	0.6656	0.0000	1.502	—
	2	1.1402	0.4128	1.184	0.56
	3	0.6216	0.3245	2.138	0.92
-	-	-----	-----	-----	---

Figure 11 - Bessel Coefficients

From the coefficients table, a 5th order filter will utilise n5, stage 1,2 and 3. The filter is cascading; therefore the 5th order is achieved by adding the three stages together.

Capacitor value 2.5nF

Frequency 60kHz

Stage 1

$$R_1 = \frac{a_1}{2\pi f_c C_1}$$

$$= \frac{0.6656}{2\pi \times 60k \times 2.5n} \Omega$$

$$R_1 = 706.2\Omega$$

Stage 2

$$C_2 \geq \frac{C_1 \times 4b}{a^2}$$

$$\geq \frac{2.5n \times 4 \times 0.4128}{(0.6656)^2} \geq 3.18nF$$

$$C_2 = 3.2nF$$

$$R = \frac{a_i C_2 \pm \sqrt{a_i^2 C_2^2 - 4b_i C_1 C_2}}{4\pi f_c C_1 C_2}$$

$$R1 = \frac{1.1402 \times 3.2n - \sqrt{(1.1402 \times 3.2n)^2 - 4 \times 0.4128 \times 2.5n \times 3.2n}}{4\pi \times 60k \times 2.5n \times 3.2n} = 582\Omega$$

$$R2 = \frac{1.1402 \times 3.2n + \sqrt{(1.1402 \times 3.2n)^2 - 4 \times 0.4128 \times 2.5n \times 3.2n}}{4\pi \times 60k \times 2.5n \times 3.2n} = 628\Omega$$

Stage 3

$$C_2 \geq \frac{C_1 \times 4b}{a^2} = 8.3nF$$

$$C_2 = 8.4nF$$

$$R1 = \frac{0.6216 \times 8.4n - \sqrt{(0.6216 \times 8.4n)^2 - 4 \times 0.3245 \times 2.5n \times 8.4n}}{4\pi \times 60k \times 2.5n \times 8.4n} = 325\Omega$$

$$R2 = \frac{0.6216 \times 8.4n + \sqrt{(0.6216 \times 8.4n)^2 - 4 \times 0.3245 \times 2.5n \times 8.4n}}{4\pi \times 60k \times 2.5n \times 8.4n} = 334\Omega$$

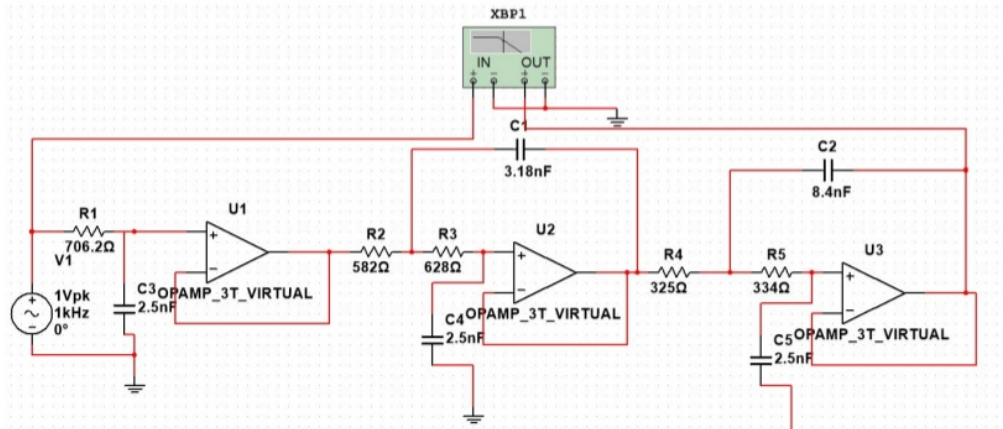


Figure 12 - 5th Order Bessel filter

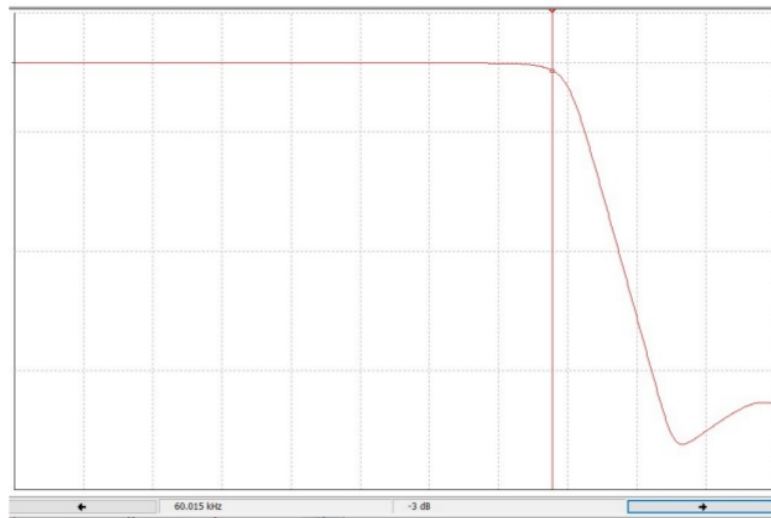


Figure 13 - 5th order Bessel cut-off

Shows cut-off at 60KHz

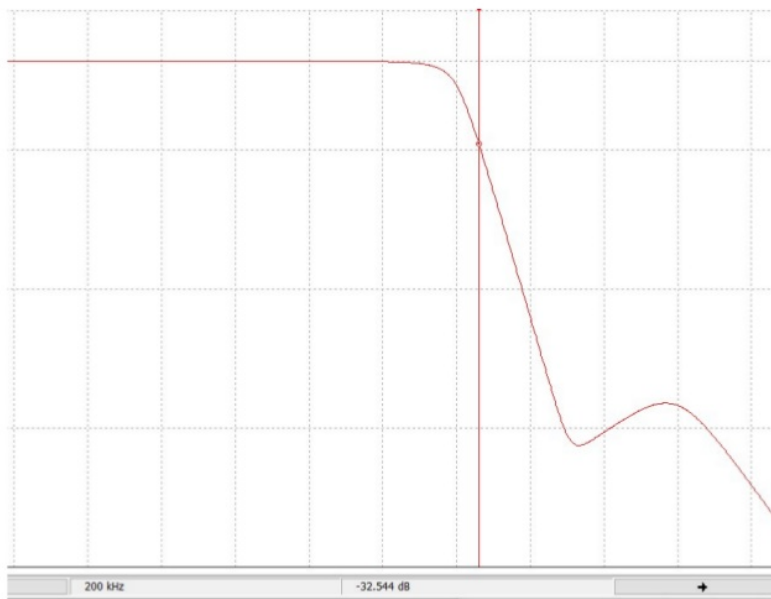


Figure 14 - 5th order Bessel Roll-off measurement starting at 200KHz

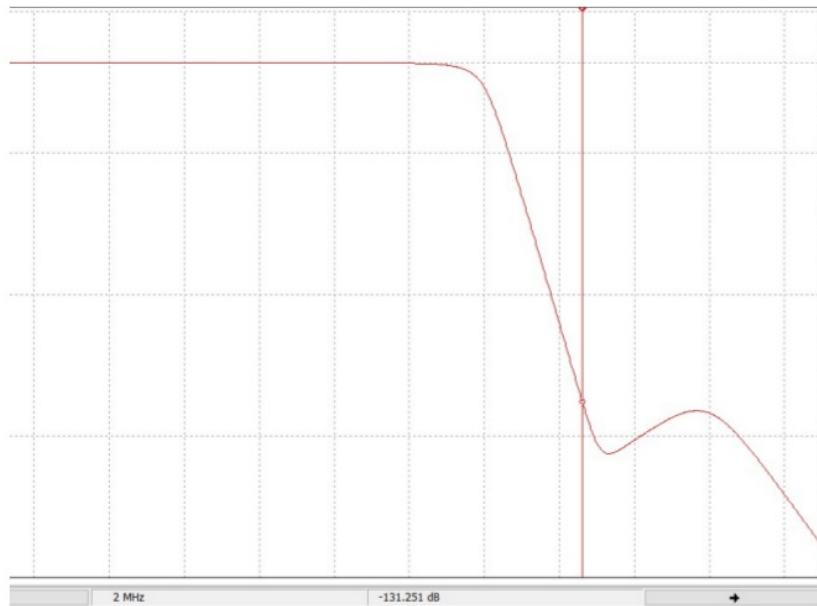


Figure 15 - 5th Order Bessel roll-off measurement at 2MHz

Shows roll-off of -98.7dB/decade

Butterworth

Butterworth coefficients

Table 16–5. Butterworth Coefficients

n	i	a _i	b _i	k _i = f _{ci} /f _c	Q _i
1	1	1.0000	0.0000	1.000	—
2	1	1.4142	1.0000	1.000	0.71
3	1	1.0000	0.0000	1.000	—
	2	1.0000	1.0000	1.272	1.00
4	1	1.8478	1.0000	0.719	0.54
	2	0.7654	1.0000	1.390	1.31
5	1	1.0000	0.0000	1.000	—
	2	1.6180	1.0000	0.859	0.62
	3	0.6180	1.0000	1.448	1.62

Figure 16 - Butterworth filter coefficients

Stage 1

$$R_1 = \frac{a_1}{2\pi f_c C_1}$$

$$= \frac{1}{2\pi \times 60k \times 2.5n}$$

$$R_2 = 1.06K\Omega$$

Stage 2

$$C_2 \geq \frac{C_1 \times 4b}{a^2}$$

$$\geq \frac{2.5n \times 4}{(1.618)^2} \geq 3.819nF$$

$$C_2 = 3.82nF$$

$$R = \frac{a_i C_2 \pm \sqrt{a_i^2 C_2^2 - 4b_i C_1 C_2}}{4\pi f_c C_1 C_2}$$

$$R1 = \frac{1.618 \times 3.82n - \sqrt{(1.618 \times 3.82n)^2 - 4 \times 1 \times 2.5n \times 3.82n}}{4\pi \times 60k \times 2.5n \times 3.82n} = 852\Omega$$

$$R2 = \frac{1.618 \times 3.82n + \sqrt{(1.618 \times 3.82n)^2 - 4 \times 1 \times 2.5n \times 3.82n}}{4\pi \times 60k \times 2.5n \times 3.82n} = 864\Omega$$

Stage 3

$$C_2 \geq \frac{C_1 \times 4b}{a^2}$$

$$\geq \frac{2.5n \times 4}{(0.618)^2} \geq 26.18nF$$

$$C_2 = 27nF$$

$$R = \frac{a_i C_2 \pm \sqrt{a_i^2 C_2^2 - 4b_i C_1 C_2}}{4\pi f_c C_1 C_2}$$

$$R1 = \frac{0.618 \times 27n - \sqrt{(0.618 \times 27n)^2 - 4 \times 1 \times 2.5n \times 27n}}{4\pi \times 60k \times 2.5n \times 27n} = 271\Omega$$

$$R2 = \frac{0.618 \times 27n + \sqrt{(0.618 \times 27n)^2 - 4 \times 1 \times 2.5n \times 27n}}{4\pi \times 60k \times 2.5n \times 27n} = 385\Omega$$

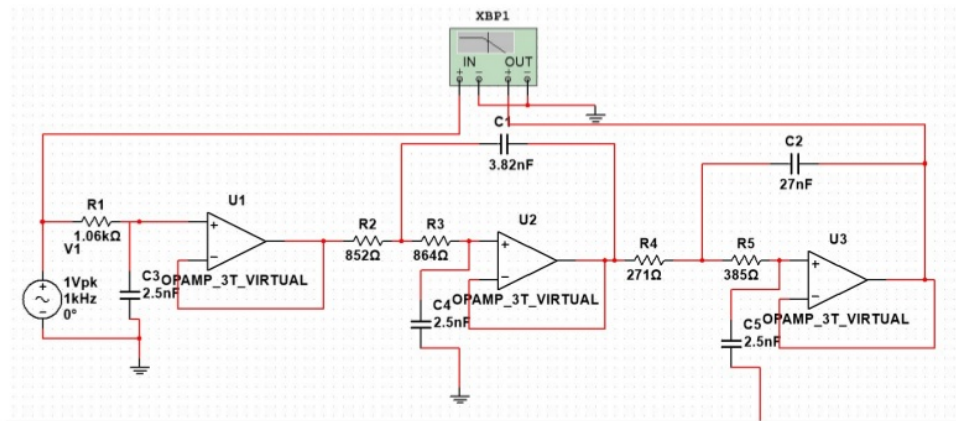


Figure 17 - 5th Order Butterworth circuit

Cut-off at -3dB, 59.981 KHz

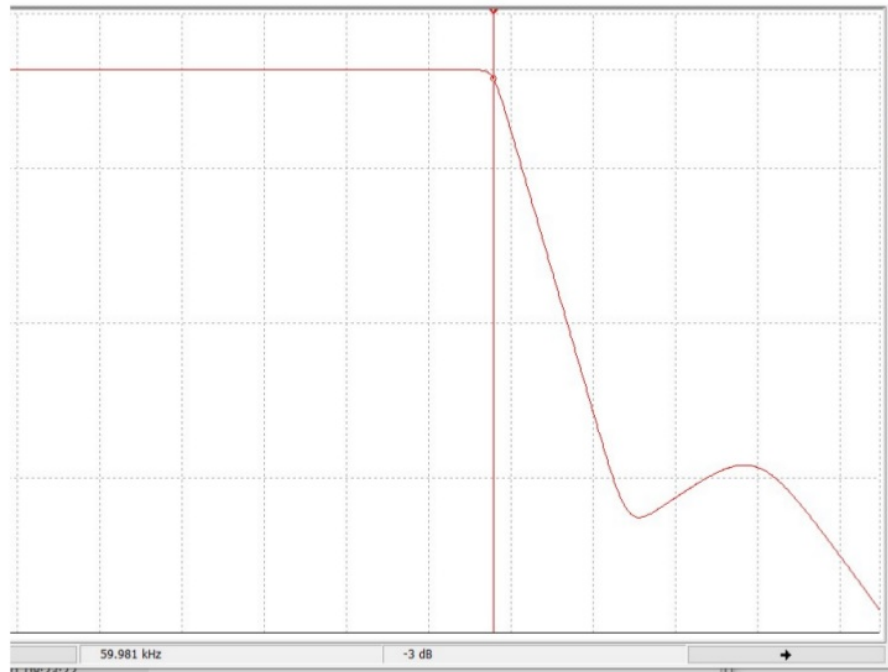


Figure 18 - 5th Order Butterworth filter cut-off

Roll-off at -99.814dB / Decade.

By measuring the dB value at 150KHz, -39.814dB and comparing that value with the dB value at 1.5MHz (increase of 1decade), which is -139.614 the roll-off value can be seen to be -99.814dB.

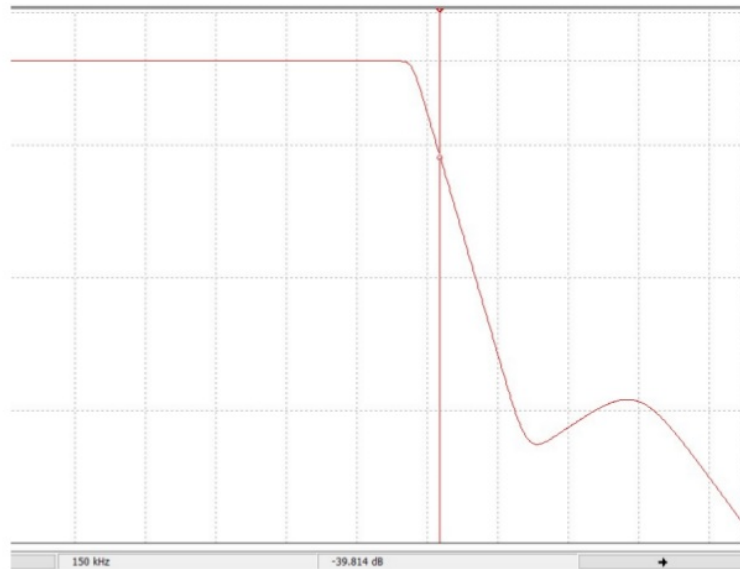


Figure 19 - 5th Order Butterworth roll-off measurement at 150KHz

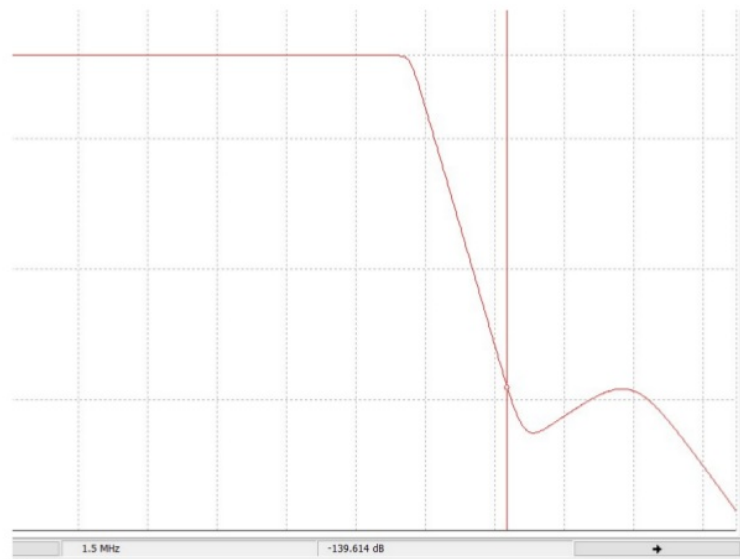


Figure 20 - 5th Order Butterworth Roll-off measurement at 1.5MHz

Tschebyescheff (-1dB Ripple)

Stage 1

$$R_1 = \frac{a_1}{2\pi f_c C_1}$$
$$= \frac{3.5711}{2\pi \times 60k \times 2.5n}$$

$$R_2 = 3.78k\Omega$$

Stage 2

$$C_2 \geq \frac{C_1 \times 4b}{a^2}$$

$$\geq \frac{2.5n \times 4 \times 2.4896}{(1.1280)^2} \geq 19.5nF$$

$$C_2 = 20nF$$

$$R = \frac{a_i C_2 \pm \sqrt{a_i^2 C_2^2 - 4b_i C_1 C_2}}{4\pi f_c C_1 C_2}$$
$$R1 = \frac{1.1280 \times 20n - \sqrt{(1.1280 \times 20n)^2 - 4 \times 2.4896 \times 2.5n \times 20n}}{4\pi \times 60k \times 2.5n \times 20n} = 510\Omega$$
$$R1 = \frac{1.1280 \times 20n + \sqrt{(1.1280 \times 20n)^2 - 4 \times 2.4896 \times 2.5n \times 20n}}{4\pi \times 60k \times 2.5n \times 20n} = 687\Omega$$

Stage 3

$$C_2 \geq \frac{C_1 \times 4b}{a^2}$$

$$\geq \frac{2.5n \times 4 \times 1.0814}{(0.1872)^2} \geq 308.6nF$$

$$C_2 = 320nF$$

$$R = \frac{a_i C_2 \pm \sqrt{a_i^2 C_2^2 - 4b_i C_1 C_2}}{4\pi f_c C_1 C_2}$$
$$R1 = \frac{0.1872 \times 320n - \sqrt{(0.1872 \times 320n)^2 - 4 \times 1 \times 2.5n \times 320n}}{4\pi \times 60k \times 2.5n \times 320n} = 92.6\Omega$$
$$R1 = \frac{0.1872 \times 320n + \sqrt{(0.1872 \times 320n)^2 - 4 \times 1 \times 2.5n \times 320n}}{4\pi \times 60k \times 2.5n \times 320n} = 106\Omega$$

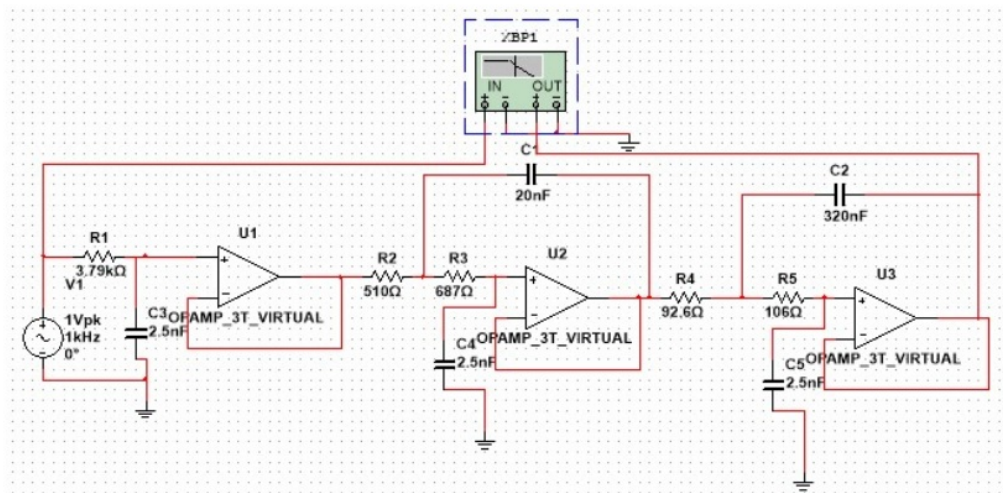


Figure 21 5th order Tschebyscheff filter coefficients

Cut-off at -3dB 59.614KHz

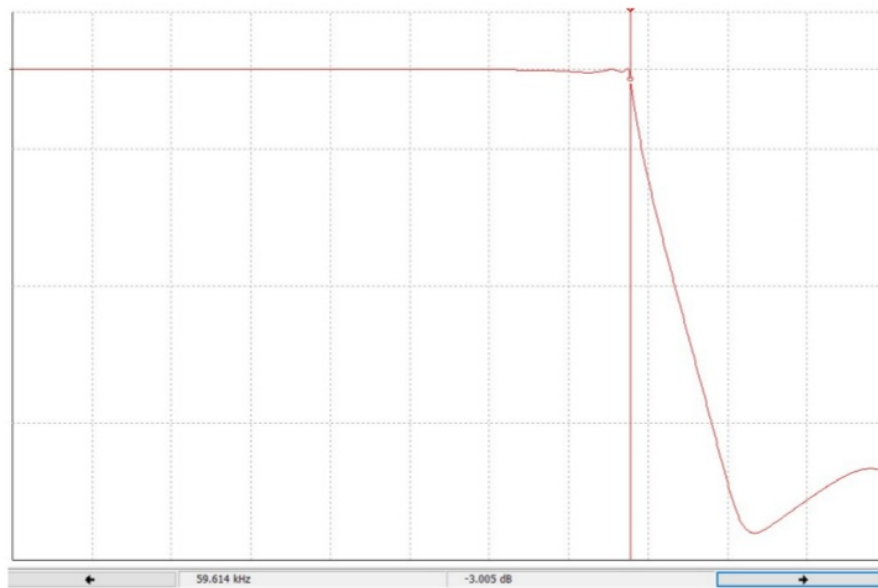


Figure 22 - Cut-off

Roll-off values taken at 100KHz and 1MHz, resulting in -104.965dB roll-off value.

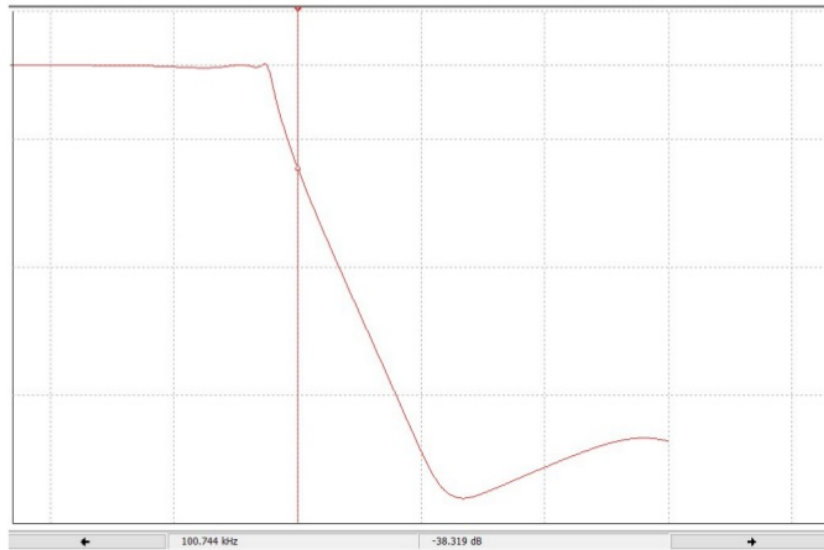


Figure 23 - Roll-off start measurement at 100KHz

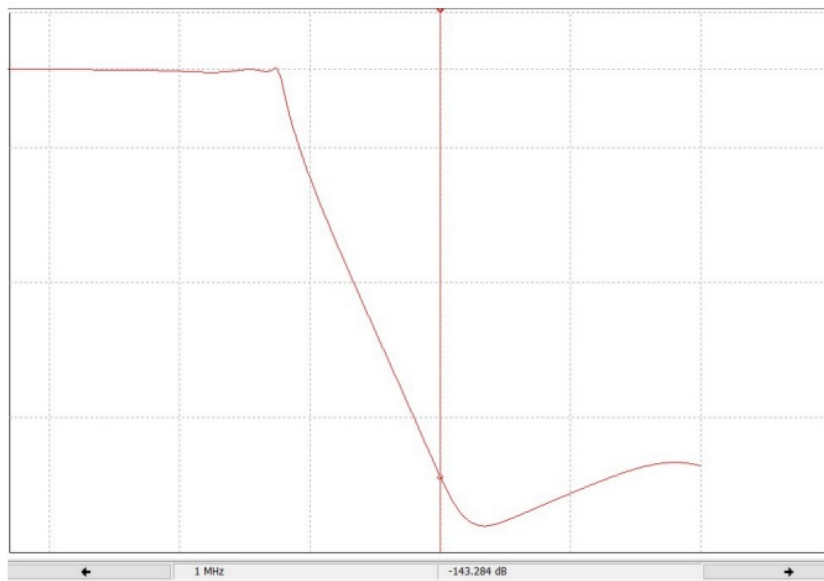


Figure 24 - Roll-off end measurement at 1MHz

HIGH PASS BUTTERWORTH

The circuit design of the high pass Butterworth filter will be the same as the low pass filter, with the exception of the inductor-capacitor layout. High-pass filters use a series capacitors and shunt inductors, as illustrated in figure 25.

3rd order high pass Butterworth

Stage 1

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{2\pi 60k(1n)1} = 2.65K\Omega$$

$$R2 = \frac{a_1}{4\pi f_c C b_1} = \frac{1}{4\pi 60k(1n)0} = n/a$$

Stage 2

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{2\pi 60k(1n)1} = 5.3K\Omega$$

$$R2 = \frac{a_1}{4\pi f_c C b_1} = \frac{1}{4\pi 60k(1n)1} = 1.33K\Omega$$

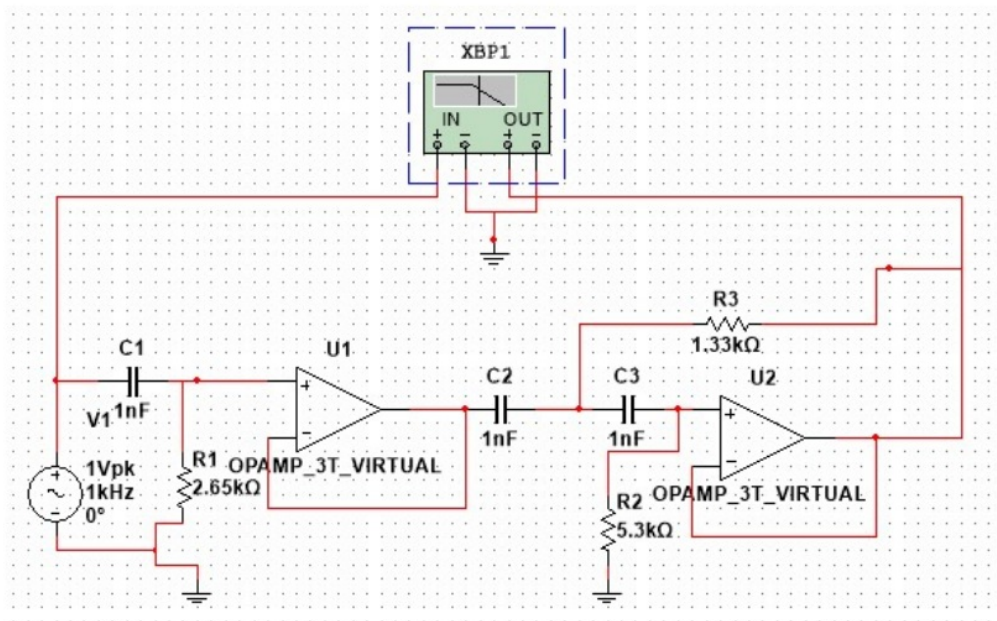


Figure 25 3rd Order Butterworth High pass filter

Figure 26 shows the cut-off frequency at 60KHz as expected.

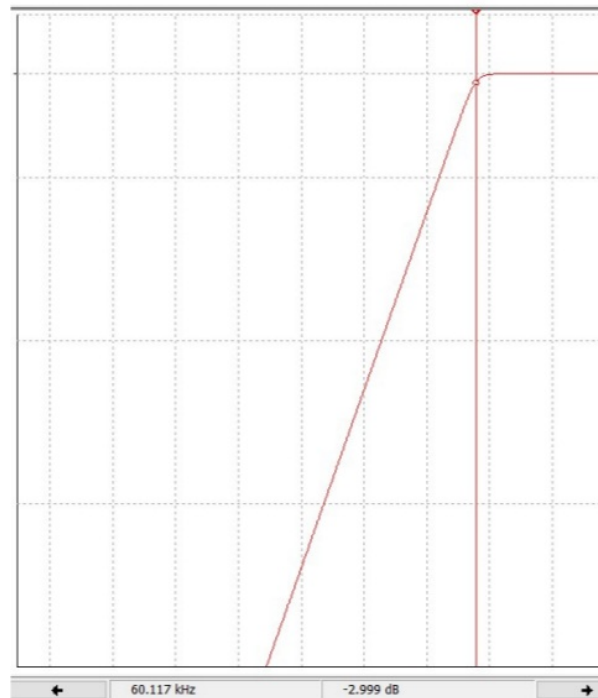


Figure 26 - 3rd Order high pass Butterworth filter cut-off

The 3rd order filter should result in -60dB roll-off, figures 27 & 28 show that this is correct. Simulated value is -60.405dB.

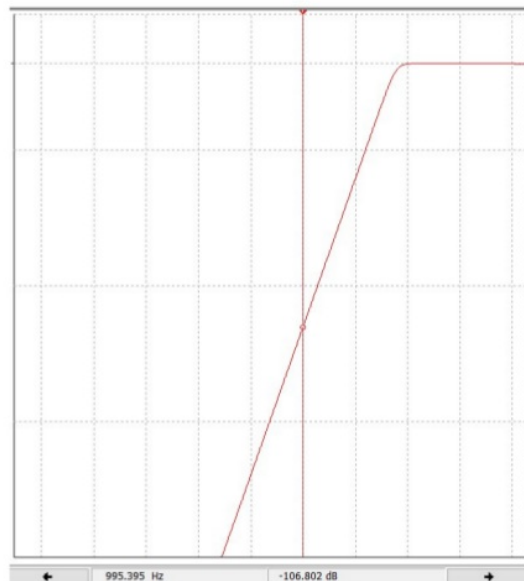


Figure 27 - 3rd order high pass Butterworth roll-off measurement

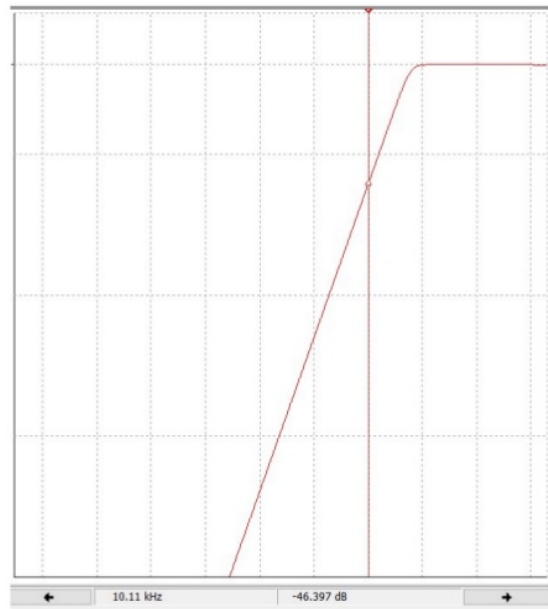


Figure 28 - 3rd Order high pass Butterworth Roll-off measurement at 10KHz

6th Order Butterworth

Stage 1

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{\pi 60k(1n)1.9319} = 2746 \Omega$$

$$R2 = \frac{a_1}{4\pi f_c C b_1} = \frac{1.9319}{4\pi 60k(1n)1} = 2562 \Omega$$

Stage 2

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{2\pi 60k(1n)1.4142} = 3751 \Omega$$

$$R2 = \frac{a_1}{4\pi f_c C b_1} = \frac{1.4142}{4\pi 60k(1n)1} = 1875 \Omega$$

Stage 3

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{2\pi 60k(1n)0.5176} = 10249 \Omega$$

$$R2 = \frac{a_1}{4\pi f_c C b_1} = \frac{0.5176}{4\pi 60k(1n)1} = 868 \Omega$$

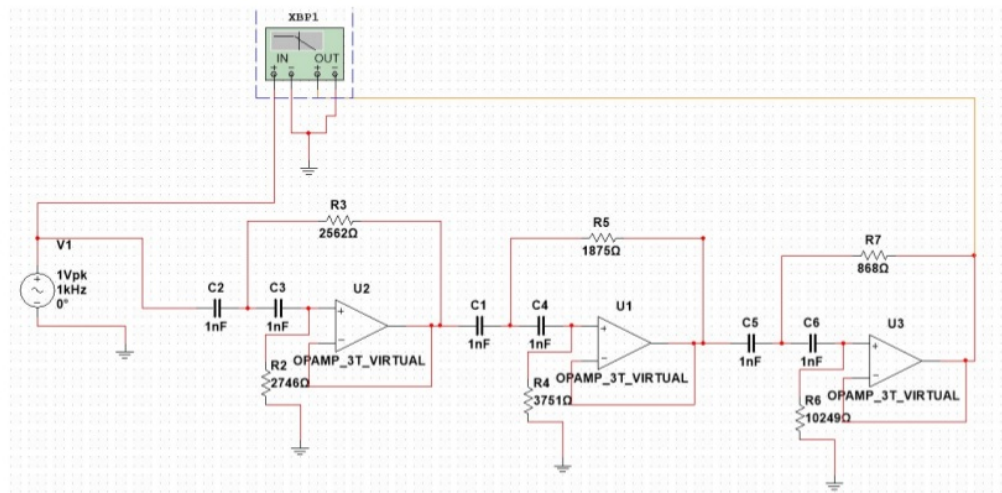


Figure 29 - 6th Order High pass Butterworth filter circuit

Figure 30 shows the cut-off frequency to be 63KHz at -3dB.

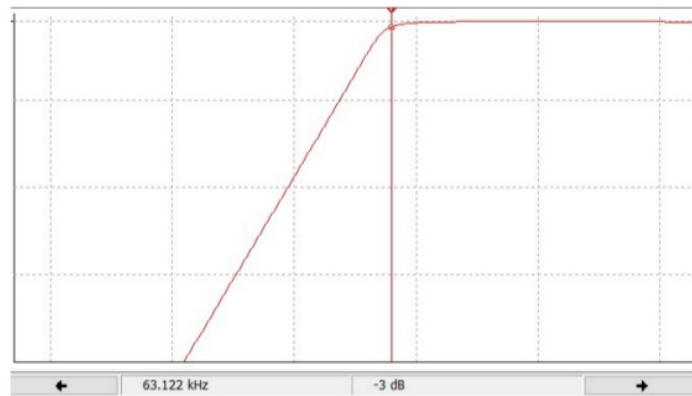


Figure 30 - 6th Order high pass Butterworth cut-off

Figures 31 & 32 below show the simulated roll-off to be -120dB per decade, as expected.

Where $-175.22\text{dB} - 55.037\text{dB} = -120.183\text{dB}$.

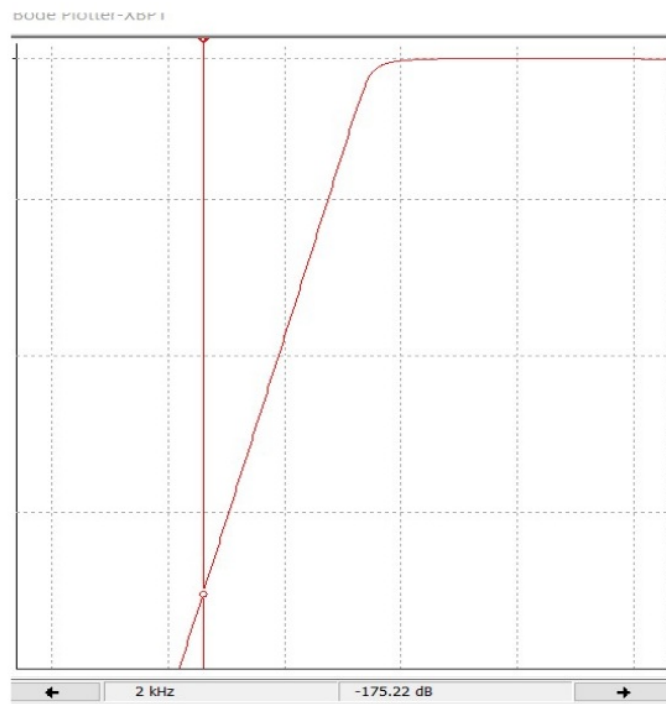


Figure 31 - Roll-off measurement start at 2KHz

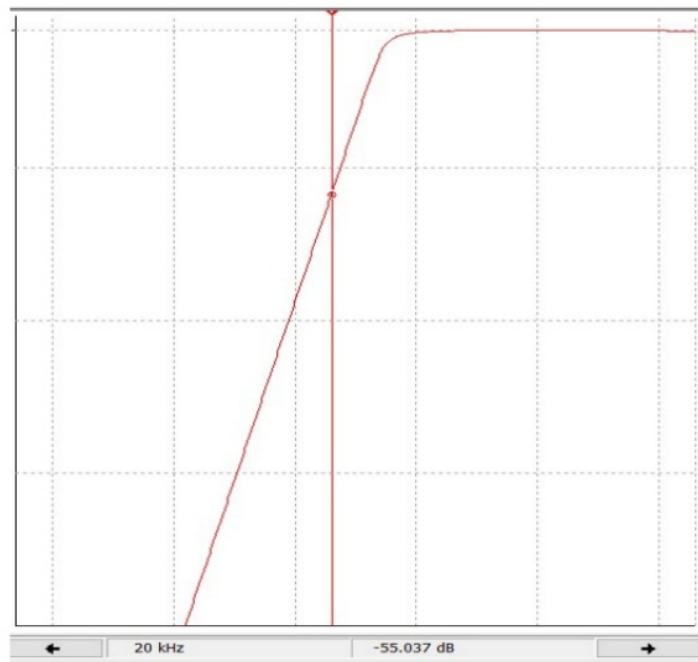


Figure 32 - Roll-off measurement at 20KHz

9th order Butterworth

Stage 1

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{2\pi 60k(1n)1} = 2650 \Omega$$

$$R2 = \frac{a_1}{4\pi f_c C b_1} = \frac{1}{4\pi 60k(1n)0} = n/a$$

Stage 2

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{2\pi 60k(1n)1.8794} = 2820 \Omega$$

$$R2 = \frac{a_1}{4\pi f_c C b_1} = \frac{1.8794}{4\pi 60k(1n)1} = 2490 \Omega$$

Stage 3

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{2\pi 60k(1n)1.5321} = 3460 \Omega$$

$$R2 = \frac{a_1}{4\pi f_c C b_1} = \frac{1.5321}{4\pi 60k(1n)1} = 2030 \Omega$$

Stage 4

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{2\pi 60k(1n)1} = 5310 \Omega$$

$$R2 = \frac{a_1}{4\pi f_c C b_1} = \frac{1}{4\pi 60k(1n)1} = 1330 \Omega$$

Stage 5

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{2\pi 60k(1n)0.3473} = 15300 \Omega$$

$$R2 = \frac{a_1}{4\pi f_c C b_1} = \frac{0.3473}{4\pi 60k(1n)1} = 461 \Omega$$

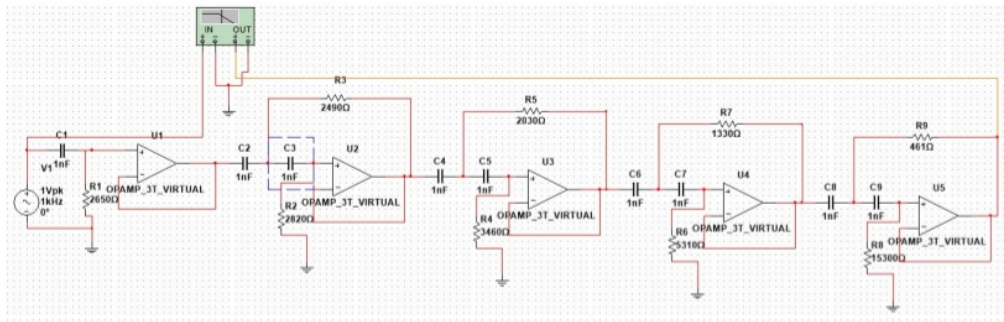


Figure 33 - 9th Order high pass Butterworth filter circuit

Cut-off frequency simulated and confirmed to be 60KHz at -3dB, as shown in figure 34

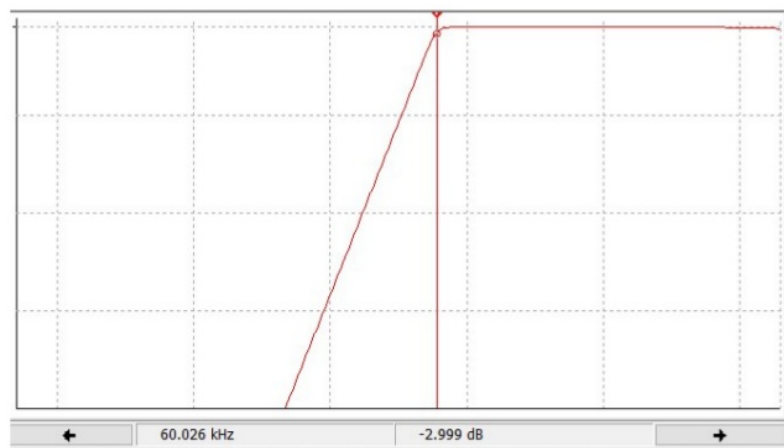


Figure 34 - Cut-off

The roll-off for a 9th order filter should be -180dB. This value is confirmed on the simulation shown in figure 35 & 36. The roll-off is calculated to be -180.033dB.

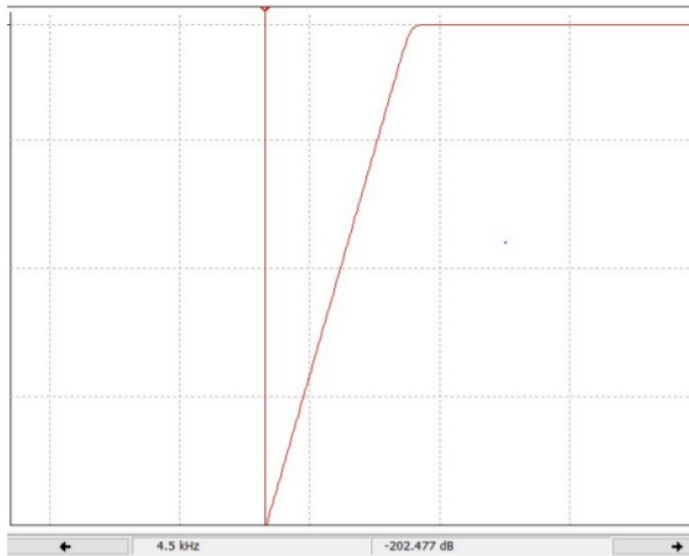


Figure 35 - Roll-off start measurement at 4.5KHz

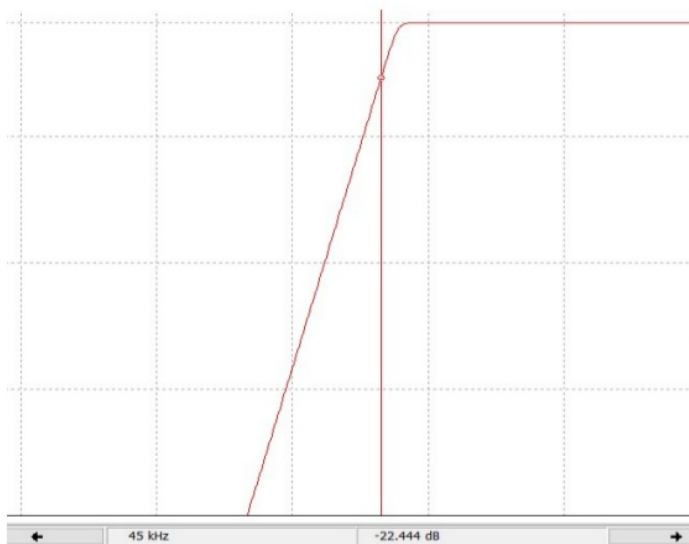


Figure 36 - Roll-off measurement at 45KHz

4. Testing and improving the design

The cascading filters cut-off frequency at -3dB should be 60KHz. The expected Roll-off for cascading filters is -20dB per decade, per order, therefore a 5th Order filter should exhibit -100dB/decade roll-off. A 3rd, 6th and 9th order filter should exhibit -60dB, 120dB and 180dB respectively.

The circuits were simulated and the measured results compared to expected results, as seen in table 1 below.

5th Order	Bessel			Butterworth			Tschebyscheff		
	Expected	Actual	Acceptable?	Expected	Actual	Acceptable?	Expected	Actual	Acceptable?
Cut-off frequency @ -3dB	60KHz	60.015KHz	Yes	60KHz	59.981KHz	Yes	60KHz	59.614KHz	Yes
Roll-off	-100dB	-98.7dB	Yes	-100dB	-99.814dB	Yes	-100dB	-104.965dB	Yes
Shape	Gradual decay after cut-off	Gradual decay after cut-off	yes	Exponential decay after cut-off - no peaking	Exponential decay after cut-off - no peaking	yes	Exponential decay after cut-off with pass band ripple	Exponential decay after cut-off with pass band ripple	yes
Pass-Band characteristic	No ripple	No ripple	yes	No Ripple	No Ripple	yes	-1dB Ripple	-1dB Ripple	yes

Table 1 - Table of results

The figure below shows the response of the three-5th order low pass filters.

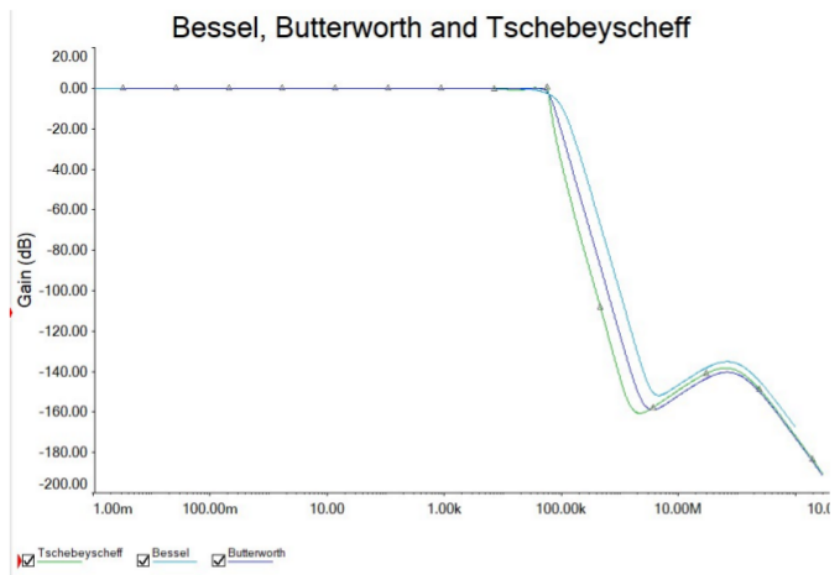


Figure 37 - 5th order filters combined response

Figure 38 shows the pass band response of the three-5th order low pass filters. It is clear from this graph that the filters responded in cohesion with the published data, where the Tschebyscheff shows pass band ripple, Bessel shows a gradual curve through pass band to cut-off and the Butterworth is maximally flat.

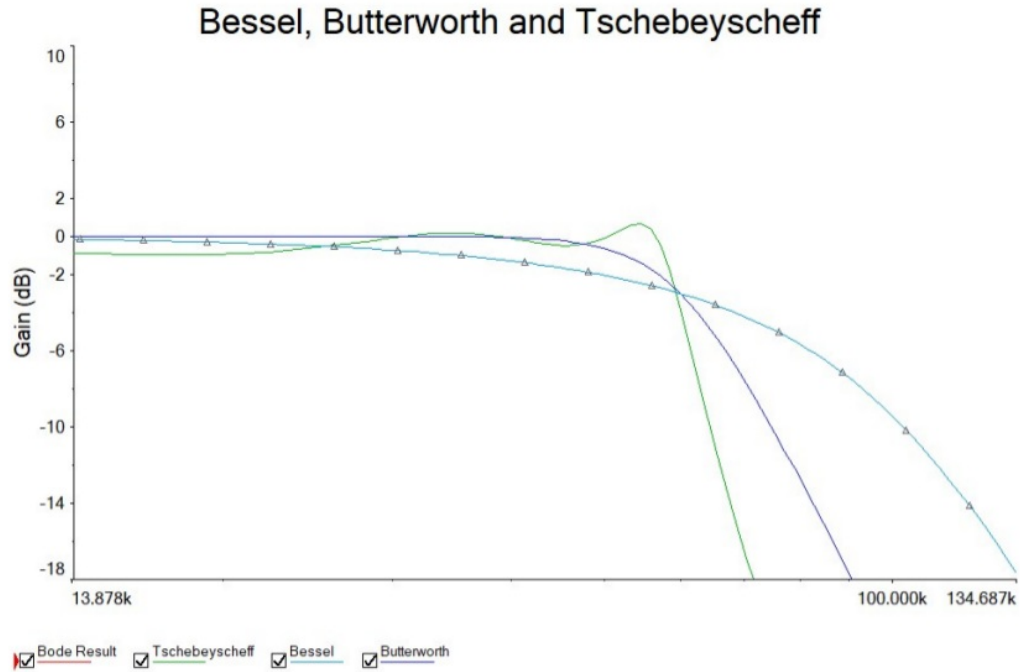


Figure 38 - Pass band characteristics of the 5th order low pass filters

Table 2 shows the 3rd, 6th and 9th order high-pass Butterworth results;

Butterworth high pass	Cut-off		Roll-off	
	Expected	Simulated	Expected	Simulated
3rd Order	60KHz	60.117KHz	-60dB	-60.405dB
6th order	60KHz	63.122KHz	-120dB	-120.183dB
9th order	60KHz	60.026KHZ	-180dB	-180.033dB

Figure 39 - Butterworth high pass filters results

5. Conclusion

The filters were designed, tested and simulated, using published filter coefficients and filter design methods, including the Sallen-key unity gain topology. A wealth of knowledge has been gained through conducting in-depth research into filter properties, characteristics, behaviour and utilisation.

Noise filtering forms an integral part of many electronic systems, such as process control, audio, audio/visual and radio frequency systems. Without filtering, many of these systems will simply not be able to function in a usable manner.

The cascading low pass filters, were designed as 5th order filters, where the cut-off and roll-off measured by simulation the circuits on multisim, the results were compared to published results and found to be correct, there the roll-off for each cascading filter increased by -20dB to give the 5th order roll-off at -100dB.

The filter response characteristics in the pass band and dead band were investigated and the following conclusions were made; the Bessel filter showed a gradual or slow transition between pass-band and stop-band, whereas the Butterworth show a very flat transition through the pass-band and steep roll-off. The Tschebyscheff, in contrast to the other two filters, showed pass-band ripple, with very steep roll-off.

The high pass Butterworth filters behaved as expected, with the same amount of roll-off per filter as low-pass filters. The 3rd, 6th and 9th order high-pass filters had -60dB, -12dB and -180dB roll-off respectively with transition through pass-band, as expected.

Overall, this assignment can be deemed to have been successful, as the aims and objectives have been achieved.

References

- Aspencore, 2020. *Electronics Tutorials*. [Online]
Available at: <https://www.electronics-tutorials.ws/filter/sallen-key-filter.html>
[Accessed 05 05 2020].
- Bird, J., 2010. *Electrical Circuit Theory and Technology*. 4th ed. London: Elsevier Ltd.
- Darby, M., 2019. *Control Global*. [Online]
Available at: https://www.controlglobal.com/assets/digital_edition/2019/July/filtering.pdf
[Accessed 28 04 2020].
- Electronicshub, 2020. *Electronicshub.org*. [Online]
Available at: <https://www.electronicshub.org/butterworth-filter/>
[Accessed 27 04 2020].
- Electronicsnotes, 2020. *Electronic notes*. [Online]
Available at: <https://www.electronics-notes.com/articles/radio/rf-filters/what-is-bessel-filter-basics.php>
[Accessed 24 04 2020].
- ELPROCUS, 2020. *Elprocus*. [Online]
Available at: <https://www.elprocus.com/types-of-chebyshev-filters/>
[Accessed 05 04 2020].
- Instruments, N., 2019. *Anti-Aliasing Filters and Their Usage Explained*. [Online]
Available at: <https://www.ni.com/en-gb/innovations/white-papers/18/anti-aliasing-filters-and-their-usage-explained.html>
[Accessed 29 04 2020].
- Smith, S., 1997. Chebyshev filters. In: *The Scientist and Engineer's Guide to Digital Signal Processing*. San Diego: California Technical Publishing, p. 619.
- Thompson, M., 2014. *Science Direct*. [Online]
Available at: <https://www.sciencedirect.com/topics/engineering/bessel-filter>
[Accessed 25 04 2020].
- Wang, R., 2019. *Fourier Engineering.edu*. [Online]
Available at: fourier.eng.hmc.edu/e84/lectures/ActiveFilters/node6.html
[Accessed 26 04 2020].

FINAL GRADE

GENERAL COMMENTS

Instructor

89/100

PAGE 1

PAGE 2

PAGE 3

PAGE 4

Text Comment. Write an executive summary rather than aims and objectives.

PAGE 5

Text Comment. Include researched versions of the circuit here rather than your practicals.

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GRADING FORM: CSG-RUBIC

**LOURENS
BRITS**

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RESEARCH-INFORMED LITERATURE

 There was evidence of considerable further reading and research from highly credible and reliable sources. Your interpretation and understanding of the additional research was exceptional and demonstrated a deep underlying appreciation of the subject. Your references were consistently applied to a high level of competency and your reference list was extensive for this assignment.

9/10

KNOWLEDGE AND UNDERSTANDING

 The knowledge and understanding of the subject demonstrated by this assignment was exceptional. There were no gaps in your knowledge of the basic principles and the higher level concepts were extremely well explained. Your explanation of the design process and calculations was also excellent and you have demonstrated an exceptionally detailed knowledge and critical understanding of the main concepts and expanded your knowledge beyond that contained in the course notes.

27/30

ANALYSIS

 Your analysis of the task was outstanding, you have demonstrated highly competent analytical skills and your approach to the task was highly logical. You carried out a detailed evaluation of the results and

17/20

included an excellent conclusion connecting ideas and providing logical and persuasive arguments. You have demonstrated a considerable capacity for independent thought and the ability to see beyond the question and your interpretation of the quantitative and qualitative data was exceptional with sound judgements based on wholly valid arguments.

PRACTICAL APPLICATION AND DEP.



Your application of practical skills for this task was generally exceptional. You used both the basic and advanced features of the resources appropriately when designing the circuit and you used appropriate advanced options for testing and evaluating the circuit performance. You managed to design an effective circuit that functioned well within the specification and achieved this by rarely asking for assistance thus demonstrating some advanced problem solving skills. Your results were comprehensive and allowed for a detailed conclusion to be attempted.

27/30

SKILLS FOR PROFESSIONAL PRAC.



In this assignment you have demonstrated skills in working individually and also collaboratively. Your written report was exceptionally well structured and written in a highly coherent and logical way. The report was presented in a professional manner using appropriate language and formatting, good diagrams in appropriate places, good sentence/paragraph structure and clear calculations.

9/10

