DESIGN OF FILTERS USING CURRENT FEEDBACK OPERATIONAL AMPLIFIER (CFOA) IC AD844

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Submitted by:

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I, PREETI BASETA, Roll no., 2K16/C&I/12, student of M. Tech (CONTROL &INSTRUMANTAION), hereby declare that the project Dissertation entitled "DESIGN OF FILTERS USING CURRENT FEEDBACK OPERATIONAL AMPLIFIER (CFOA) IC AD844" which is being submitted by me to the Department of ELECTRICAL ENGINEERING, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associate ship, Fellowship or other similar title or recognition.

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I hereby certify that the Project Dissertation titled "DESIGN OF FILTERS USING CURRENT FEEDBACK OPERATIONAL AMPLIFIER (CFOA) IC AD844" which is submitted by PREETI BASETA, Roll No 2K16/C&I/12, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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PREETI BASETA

ABSTRACT

Analog filters play a key role in any modern communication, instrumentation and electronic system. Though today the entire signal processing world seems to be digital, the presence of continuous time filters can be found at every interface with analog world.

With the evolution of several new active building blocks in open literature, there is a great advancement in active filter deign. Current Feedback Operational Amplifier is an active building block which is characterized by a very high slew rate and can be used to replace the traditional, internally compensated voltage operational amplifier (741 type) in RC active filters.

Since CFOA have gain-bandwidth independence and higher slew rate as compared to to traditional VOAs basic to higher order filter are designed using CFOA AD844. Active simulation of LC ladder is done by Operational simulation approach. The present work deals with the Realization of First order, Second order and higher order filters using CFOA. Also the gain-bandwidth independence has been proved by designing an inverting amplifier.

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LIST OF SYMBOLS, ABBREVIATIONS

S. No.	Symbols/Abbreviations	Descriptions
1.	ω_0	Natural Frequency
2.	Q	Quality Factor
3.	ASP	Analog signal Processing
4.	DSP	Digital Signal Processing
5.	Op-Amp	Operational Amplifier
6.	HP	High Pass
7.	LP	Low Pass
8.	BP	Band Pass
9.	ABB	Active Building Block
10.	OTA	Operational Transconductance Amplifier
11.	CC	Current Conveyor
12.	CFOA	Current feedback Operational Amplifier
13.	VOA	Voltage Operational Amplifier

CHAPTER 1

INTRODUCTION

The present dissertation deals with Current Feedback Operational Amplifier (CFOA) and its applications in design of active RC filters.

Signal Processing is the technology for transformation, interpretation and generation of information. Signal processing involves various applications and can be implemented in two different ways: analog signal processing and digital signal processing [1]. In all we can say about 80 percent of work in the field of electronic is carried out with help of digital signal processing, even though all signals available in nature are analog which makes analog signal processing (ASP) an interface between the real world and the digital world. In any digital signal which is interfaced to an analog signal, the presence of ASP can't be avoided because of the following reasons: first to remove aliasing before A/D conversions and second to match dynamic range of input signal to that of ADC [2]. Thus irrespective of the advances taking place in the field of digital hardware and allied software, ASP will always be required. The advancement in DSP also poses new challenges to ASP as the requirements of advanced interfacing circuits are dealt by ASP only.

The selection between DSP and ASP depends on our requirements. DSP provides programmability, higher accuracy, ease of storage and low cost implementation making it an obvious choice in low cost applications; but under certain circumstances ASP provides more efficient solution and it may be the only available solution!. Signals with larger bandwidth require faster A/D converter and faster digital signal processor. To fulfil these requirements the digital hardware which is needed is not practically realizable [3].These types of signals can be processed more efficiently with ASP. Though ASP is faster than DSP, it has some disadvantages. These include: less flexibility, requirement of more expensive components, amplifier drifts, and absence of modular design concepts. In ASP, wide range of operations are performed such as filtering, amplification, signal generation, addition, comparison, division, multiplication, synchronous detection, noise reduction, minimization etc. It also deals with conversion of signals from one analog domain to another viz. voltage to current, current to voltage and ac to dc etc. These wide ranges of operations are possible due to availability of large amount of active elements known as Active Building Blocks (ABBs).

1.1 FUNDAMENTALS OF FILTERS

A filter is basically a frequency selective circuit which allows the reshaping of frequency spectrum of an input signal. In general, it is a device which passes certain frequencies which are required by the designer while rejects other. Quantities of interest in electrical engineering are basically voltage and current signal. Any voltage and current signal can be thought of as comprising of various frequency components(0-∞). Thus an electronic/electrical filter passes the signal in certain frequency range and attenuates the signal in other frequency ranges [6]. The set of frequencies which are allowed to pass through the filter is termed as "Passband" while the set of frequencies which are attenuated by the filter is termed as "Stopband". The region which lies between Passband and Stopband, is called as "Transition band". Main aim of most of the filters is to modify amplitude response so that a set of frequencies can be attenuated or blocked while other set of frequencies can pass unchanged. In certain cases the filter is required to modify the phase response also.

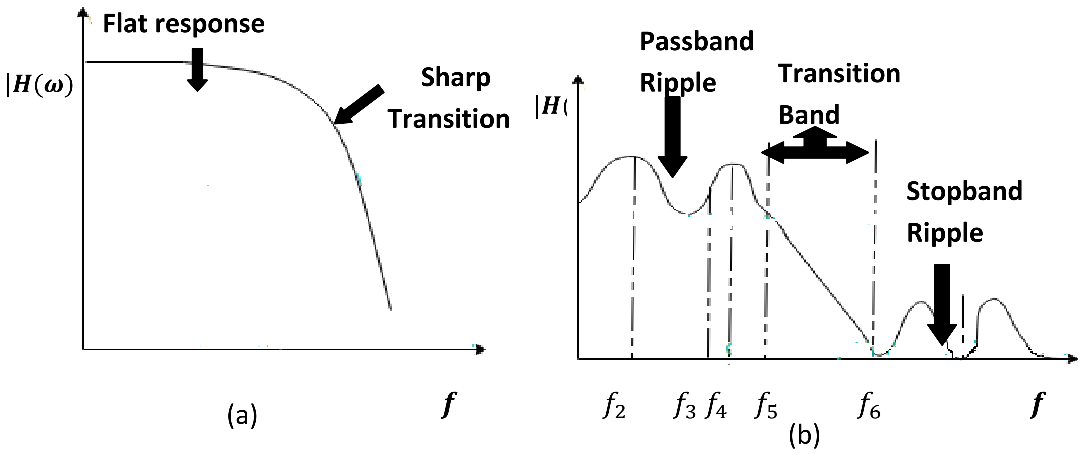


Fig. 1.1 (a) Ideal (b) Real filter characteristics

A filter provides flat frequency response in the passband with no gain or sometime some gain while it attenuates the signal in stopband. Characteristics of filter specifying all the three regions are shown in Fig. 1.1[7].

The presence of the transition band represents the fact that the movement from passband to stopband cannot be abrupt in any physically realizable filter(order of such a filter will be infinite). For the higher selectivity of the filter this band should be very narrow. The ripples in the stopband are a very significant feature so band attenuation should be large enough to suppress the interferer below the signal level. In fig 1.1(b) the attenuation is degraded between f_5 and f_6 because of the presence of ripples in stopband.

The "flatness" of the filter in the passband is described by the amount of "ripples" in its magnitude frequency response curve. If there are very large amount of ripples the contents of frequency degrades. In fig.1.1 (b), the signal frequencies between f_2 and f_3 are attenuated while those of f_3 and f_4 are amplified..

1.2 CLASSIFICATION OF FILTERS

Classification of filters can be done on different aspects. These aspects can be according to the components used in their implementation or frequency band they pass though them [6].Classification of filters based on frequency characteristics

Usually filters are classified on the basis of set of frequencies that are blocked or passed by them. Generally, the ideal characteristics of the four major filters (referred as Brick Wall) are the low–pass (LP) filter (which passes low frequencies), the high–pass (HP) filter (which passes high frequencies), the band–pass (BP) filter that passes a limited range of mid band frequencies, and the Band Elimination (BE) filter (which is a type of band–stop filter that acts on a particularly narrow range of mid band frequencies). Table 1 shows the characteristics of all the filters mentioned above [5]. In addition a very useful class of magnitude response also exists wherein the magnitude remains constant while the phase response changes with frequency such a filter is known as all-pass filter (AP).

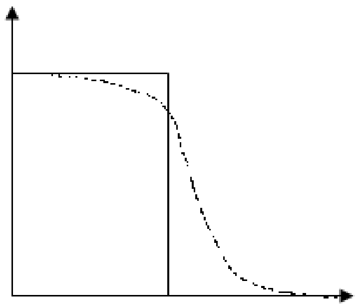
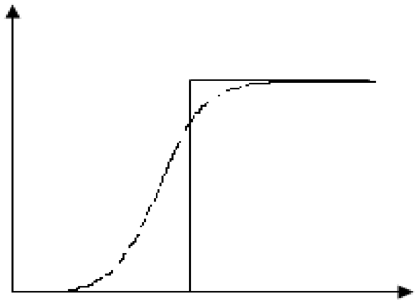
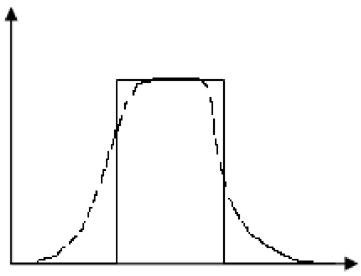
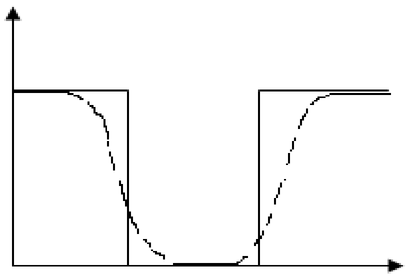
LOW PASS	HIGH PASS
	
BAND PASS	BAND STOP
	

Table 1 Frequency Response of the Four Basic Filter Types. Ideal characteristics; Real characteristics.

a. Low Pass Filter

A low pass filter allows frequencies that are less than a specified cut-off frequency to pass through it but it blocks the frequencies above the cut-off frequency. A low pass filter is used for attenuating unwanted high frequency signals while passing the low frequency signals. Low pass filters are also called as treble cut filters. A low pass filter is a circuit is designed to extend pass band from $\omega = 0$ to its cut off frequency represented by ω_c.

One example of a mechanical low pass filter is physical barrier which acts as a low pass for waves. Sometimes we noticed that the very loud music playing in someone’s house is heard as very low music sound by the neighboring member.

Low–pass filters are also used in subwoofers and other types of speaker systems to block high pitches that they cannot efficiently reproduce. In radio transmitters harmonic emissions cause interference with other communications so we use low pass filter to block them.

b. High Pass Filter

A high pass filter passes frequencies above a specified cut-off frequency but it attenuates the frequency signals below the cut-off frequency. Hence it can be used to block any unwanted low frequency components of a complex signal while passing the high frequency components. It is better known as bass-cut filter. Here the low and high frequencies are relative.

The simplest high–pass filter consists of a capacitor in series with the signal path along with a resistor parallel to the signal path. The resistance times the capacitance (*RC*) is the time constant and its reciprocal is the cut off frequency, at which the output voltage is 70.7% of the input. Such a circuit might be used in combination with a tweeter and a speaker [9].

c. Band Pass Filter

Band–pass filter passes a limited range of frequencies, and may be created as a combination of a low–pass filter and a high–pass filter .A band–pass filter will allow only frequencies to pass that are in a previously specified range. For example, an ideal band–pass filter might allow all signals to pass above 30 Hz but below 100 Hz. The signals outside this range are attenuated. But in practical case the band pass filter does not attenuated the frequency which is undesirable completely [10].

d. Band Elimination Filter

A band elimination filter is also called as Notch/band stop filter. It is generally used when the high frequency and the low frequency have 1 to 2 decades difference between them. In other words we can say that high frequency is 10 to 20 times less than the low frequency.

e. All Pass Filter

All Pass Filter is also called as delay equalizer. It does not affect the magnitude response but alters the phase characteristics of the system. It allows all frequencies to pass through it without any change in level of amplitude. Generally this filter is described by the frequency at which it the phase shift crosses 90^0 [11].

1.2.1 Classification of filters based on components used for implementation

This class of filter classification deals with how filters are implemented. If passive components are used for implementation the filter designed are called as Passive Filters while filters designed using Active components are called as Active filters[12]. Passive components include resistors, capacitors, inductors while active components include transistors, Op-amp, OTA. An additional advantage in the active filters is their inherent gain which is offered by the active devices. The implementation of low pass filter by passive components only is shown in Fig. 1.2(a) while same implementation with an active device is shown in fig 1.2(b).In active filters loading can be eliminated by proper choice of active devices.

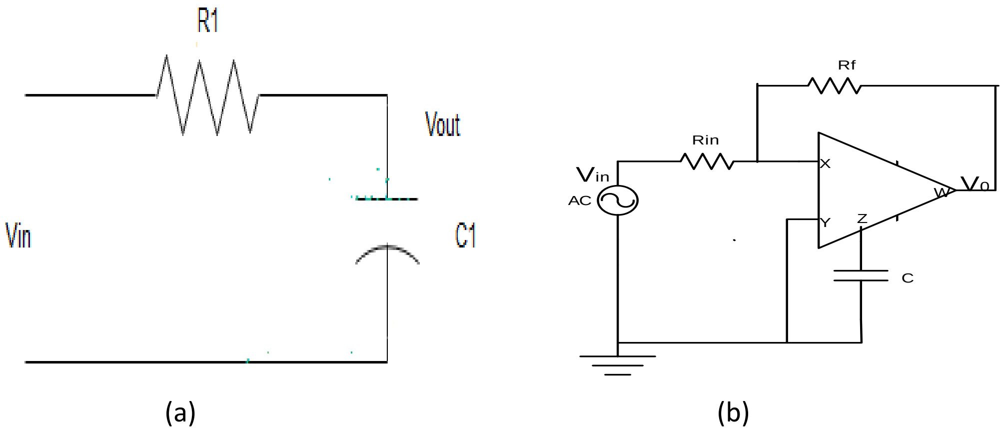


Fig 1.2 (a) Passive Low Pass filter and (b) Active low pass filter.

1.3 CHARACTERIZATION OF FILTERS

Characteristics of filters are specified usually in frequency domain by a mathematical model which is called as transfer function. The highest power of s in the denominator is called as the order of the filter. Mostly standard configurations are used to realize second order filter. The ω_0 represents the cut-off frequency and K represents the constant dc gain of the circuit. Q here is the Q-factor of the filter [13].

1.3.1 Specification of First order Filters

A first order filter can be specified according to two parameters; cut off frequency and gain. The first order transfer function is given as:”

$$T(s) = \frac{a_1 s + a_0}{s + \omega_0} \tag{1.1}$$

Here the values of a_1 and a_0 determine the filter response and ω_0 represents the natural frequency. The standard low pass filter transfer function can be evaluated by equating $a_1 = 0$ in Eq.(1.1). Thus

$$T_{LP}(s) = \frac{a_0}{s+\omega_0} \tag{1.2}$$

Similarly the high pass output can be obtained by putting $a_0 = 0$ in Eq.(1.1). Thus

$$T_{HP}(s) = \frac{a_1 s}{s+\omega_0} \tag{1.3}$$

Similarly the all pass output can be obtained by putting $a_0 = -1$ and $a_1 = 1$ in Eq. (1.1). Thus

$$T_{AP}(s) = \frac{a_1 s - a_0}{s+\omega_0} \tag{1.4}$$

Hence any first order filter is identified by: gain and cut off frequency.

1.3.2 Specification of second order filter:

Second order filter are also known as Biquads . A standard second order filter transfer function can be written a

$$T(s) = \frac{a_2 s^2 + a_1 s + a_0}{s^2 + \left(\frac{\omega_0}{Q}\right)s + \omega_0^2} \tag{1.5}$$

Here the constants a_0, a_1 and a_2 determine the type of filter response and they are Low Pass, High Pass, Band Pass, Band Reject and All Pass Filter. ω_0 and Q represents the natural frequency (pole frequency) and quality factor of the filters respectively.

Low Pass Filter:

If we take the value of $a_2 = 0,\ a_1 = 0\ and\ a_0 = 1$ then the resulting transfer function from Eq. 1.4 will be the transfer function of second order Low Pass Filter.

$$T(s) = \frac{a_0}{s^2 + \left(\frac{\omega_0}{Q}\right)s + \omega_0^2} \tag{1.6}$$

High Pass Filter:

If we take the value of $a_2 = 1,\ a_1 = 0\ and\ a_0 = 0$ then the resulting transfer function from Eq. 1.4 will be the transfer function of second order High Pass Filter.

$$T(s) = \frac{a_2 s^2}{s^2 + \left(\frac{\omega_0}{Q}\right)s + \omega_0^2} \tag{1.7}$$

Band Pass Filter:

If we take the value of $a_2 = 0,\ a_1 = 1\ and\ a_0 = 0$ then the resulting transfer function from Eq. 1.4 will be the transfer function of second order Band Pass Filter.

$$T(s) = \frac{a_1 s}{s^2 + \left(\frac{\omega_0}{Q}\right)s + \omega_0^2} \tag{1.8}$$

Band Reject Filter:

If we take the value of $a_2 = 0,\ a_1 = 1\ and\ a_0 = 1$ then the resulting transfer function from Eq. 1.4 will be the transfer function of second order Band Reject Filter.

$$T(s) = \frac{a_1 s + a_0}{s^2 + \left(\frac{\omega_0}{Q}\right)s + \omega_0^2} \tag{1.9}$$

All Pass Filter:

If we take the value of $a_2 = 1,\ a_1 = -1\ and\ a_0 = 1$ then the resulting transfer function from Eq. 1.4 will be the transfer function of second order Band Pass Filter.

$$T(s) = \frac{a_2 s^2 - a_1 s + a_0}{s^2 + \left(\frac{\omega_0}{Q}\right)s + \omega_0^2} \tag{1.10}$$

Thus second order filter can be specified with three parameters; natural frequency, gain and quality factor.

1.3.3 Specifications of Higher Order Filters:

In general, an n^{th}order transfer function is given as

$$T(s) = \frac{a_M s^M + a_{M-1} s^{M-1} + \cdots a_0}{s^N + b_{N-1} s^{N-1} + \cdots b_0} \tag{1.11}$$

Here N is the order of filter. For a stable response the required condition is $N \geq$ M. The Higher order filters can be specified in terms of following parameters:

i. Maximum variation allowed in passband transmission: A_{max}
ii. Passband edge: ω_p
iii. Minimum attenuation required in stopband: A_{min}
iv. Stopband edge: ω_s

1.4 CONCLUSION

In this chapter the introduction of ASP and its importance over DSP is discussed. Further this chapter is dedicated to the brief introduction of the Filters. Classification and characteristics of filters have been discussed in detail.

CHAPTER 2

CURRENT FEEDBACK OPERATIONAL AMPLIFIERS

In the previous chapter a brief overview of RC active filters was presented. In this chapter we give an overview of the current feedback operational amplifier, an integrated circuit amplifier which has many interesting features compared to the traditional Voltage Feedback amplifiers used in the design of the RC- active filters.

Current feedback op-amps,(CFOAs/CFAs) also called as operational trans-impedance amplifier are preferably used for designing analog circuits as compared to Voltage feedback op-amps(VOAs) because they exhibit a very significant characteristic which is not present in the traditional VOAs. CFOA based circuits have an ability of realizing variable gain but with constant bandwidth. Another important aspect of the CFOA is its very high slew rate which is of the order of several hundred to several thousand $V/\mu s$which is very high in comparison to 0.5 $V/\mu s$ for general purpose and most popular 741 types VOA. CFOA is very useful in designing circuits operating over much wider frequency ranges. In CFOA inverting input is sensitive to current not voltage as was the case with VOA. CFOA is a translinear current conveyor (CCII+) which is followed by voltage buffer. Thus CFOA has prominently gained attention due to its gain bandwidth independence, very high slew rates and higher frequency range of operation. One of the most popular CFOA is AD844. Recently a research monograph has appeared in open-literature in which applications of CFOA in ASP have been presented [14].

2.1 AD844: THE CFOA WITH EXTERNALLY ACCESIBLE COMPENSATING PIN

AD844 type CFOA has a compensation pin at pin no 5 which is externally accessible still it maintains the pin compatibility with VOAs. It has been fabricated using junction-isolated complementary bipolar process. It is a high speed monolithic device which has high bandwidth around 60 MHz for the gain of -1 and 33 MHz for the gain of -10. Signal response provided by the AD844 is very fast with excellent DC performance. It has very high slew rate around 2000 $V/\mu s$. AD844 is basically used in current to voltage conversion applications and as an inverting amplifier but we can also use it in non inverting and other applications Various application where it is used are Flash ADC input amplifier, High speed current DAC interfaces, Video buffers and cable drivers and pulse amplifiers. We can replace the AD844 with the much traditional VOAs because it has better AC performance, have high linearity and also have excellent pulse response. The input bias currents and offset voltage of the AD844 are laser trimmed due to which DC errors are minimized such that the drift in the offset voltage is not more than 1μ$V/\circ_C$ and the drift in input bias current is not more than 9 $nA/\circ_C$ .Internal architect of the AD844 is a translinear second generation plus type current conveyor followed by a translinear voltage buffer. A Simplified symbolic diagram is shown in fig below [14, 15].

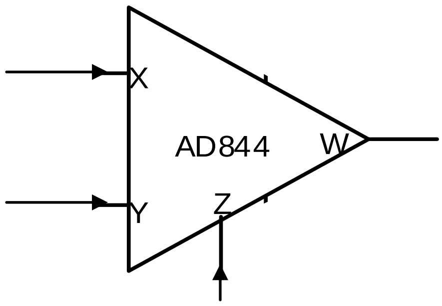


Fig 2.1 Functional Diagram of AD844 (CFOA)[14]

2.2INTERNAL ARCHITECTURE OF AD844

Internal structure of CFOA involves a second generation current conveyor followed by a voltage buffer. This made it useful to be used in place of CCII+ and CCII- as pin by pin replacement of VOA. The front end of AD844 is a CCII+ and the back end is a voltage follower so according to this we can write the terminal equations as follows.

$$I_Y = 0 \tag{2.1}$$

$$V_X = V_Y \tag{2.2}$$

$$I_Z = I_X \tag{2.3}$$

$$V_W = V_Z \tag{2.4}$$

It consists of 18 transistors. Out of 18 transistors Q_1 to Q_4 are configures as mixed translinear cell. To create a replica of current I_X collector current of the transistor Q_2 and Q_3 is sensed using two modified p-n-p and n-p-n Wilson current mirror which consist transistors Q_5 to Q_8 and Q_9 to Q_{12} respectively. This yield $I_Z = I_X$. Equal emitter currents are passed through transistors Q_1 and Q_4 by using two constant current sources. Each of them is equal to current I_B. This make the input current $I_Y = 0$ when V_Y is applied at the input terminal Y.

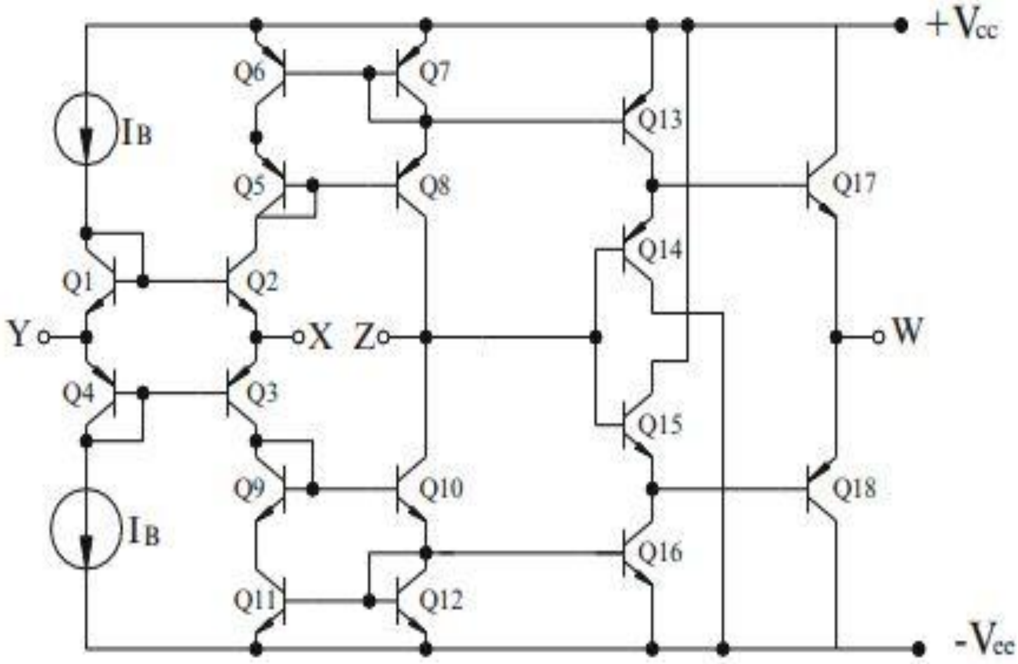


Fig 2.2 Internal Diagram of AD844 (CFOA)

2.3 INVERTING AMPLIFIER (Gain- Bandwidth Independence)

We know that all VOA-based devices have a drawback of gain bandwidth conflict. Advantage of employing CFOA is that we can overcome the gain bandwidth conflict because of the current feedback.. This means that if we change the gain of the circuit designed using CFOA its bandwidth remain unaltered. To prove this we can design an inverting amplifier. According to characteristics of CFOA $V_w = V_z = -i_z Z_P$.Here Z_P is the parasitic impedance when we look into the terminal Z of the CFOA and it consist of resistance R_p which is typically around 3MΩ and a capacitor C_p in parallel with resistance R_p. Since amplifier here is CFOA so $I_Z = I_X$

$$\frac{V_{in}-0}{R_{in}}+\frac{V_0-0}{R_f}=\frac{(0-V_0)}{R_p}+(0-V_0)sC_p \qquad (2.5)$$

$$\frac{V_o}{V_{in}}=-\frac{\frac{R_f}{R_{in}}\frac{1}{C_pR_f}}{s+\frac{1}{C_pR_f}\left(1+\frac{R_f}{R_p}\right)} \qquad (2.6)$$

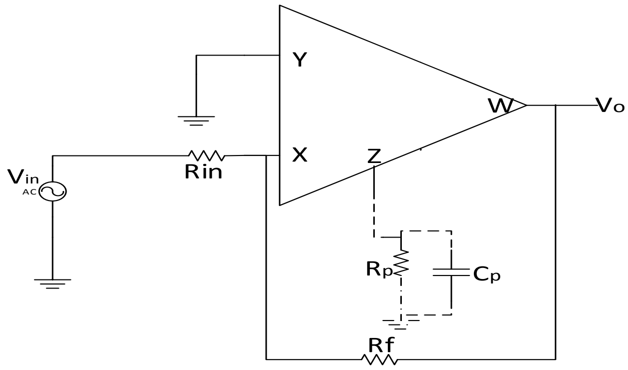


Fig 2.3 Circuit diagram of inverting amplifier

Maximum gain of this circuit is given by

$$K=\frac{R_f}{R_{in}} \qquad (2.7)$$

And the -3db cut off frequency is given by

$$\omega_{-3db}=\frac{1}{C_pR_f}\left(1+\frac{R_f}{R_p}\right)\cong\frac{1}{C_pR_f} \qquad (2.8)$$

So bandwidth of this circuit only depends on feedback resistor and gain of the circuit can be varied by varying input resistor.

Let us consider the three different values of input resistor for the fixed value of the feedback resistor. $R_f = 4K\Omega$

Case 1:-

$R_{in} = 500\Omega$ Gain $K = 8$ $\omega_{-3db} =$ 7.7MHz

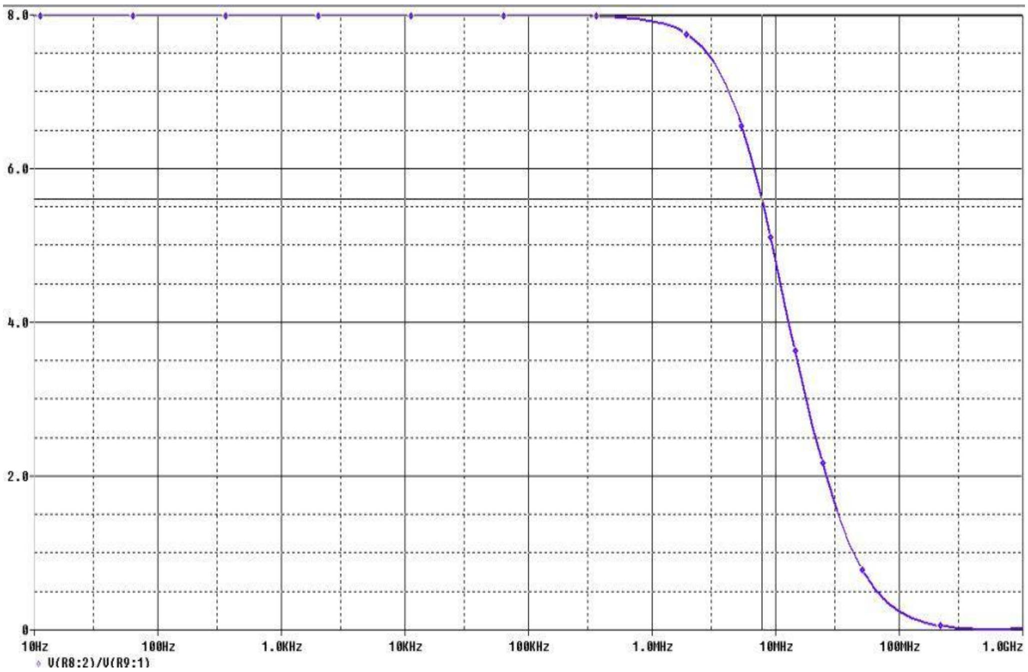
Case 2:-

$R_{in} = 1K\Omega$ Gain $K = 4$ $\omega_{-3db} =$ 8.1MHz

Case 3:-

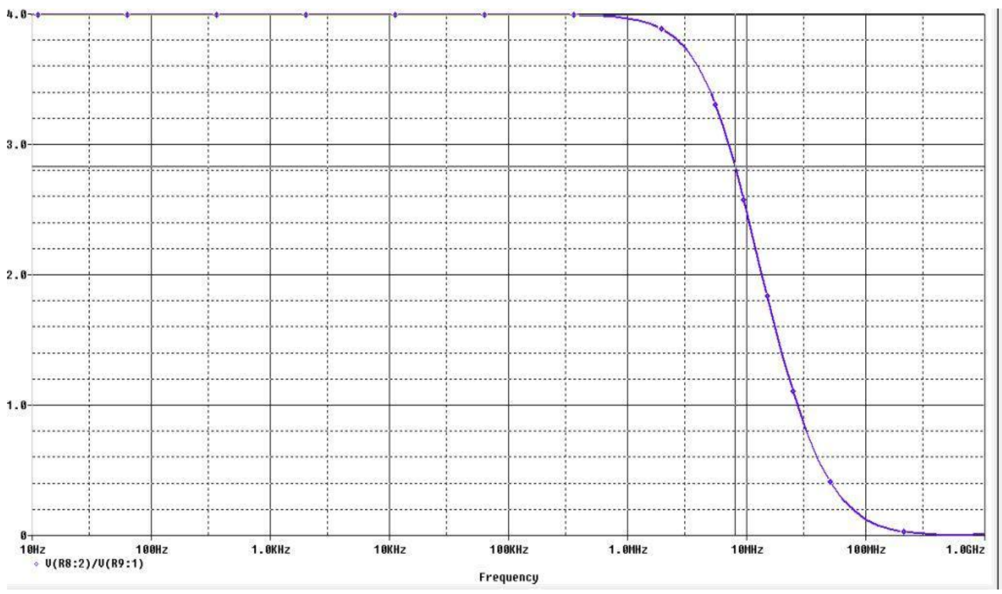
$R_{in} = 2K\Omega$ Gain $K = 2$ $\omega_{-3db} =$ 8MHz

So we noticed that bandwidth of the circuit is constant but the gain is varying. The simulation results with above components value have been shown below



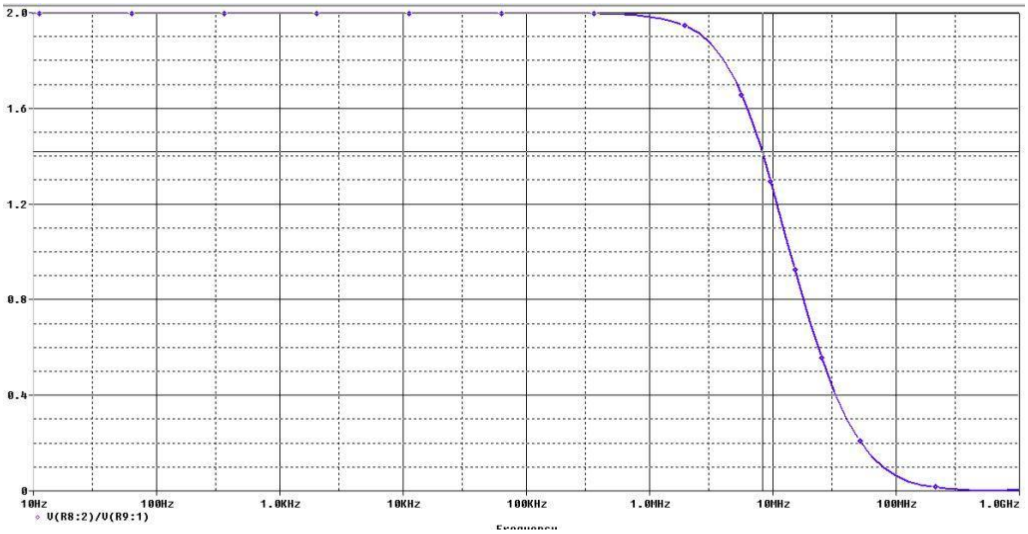
Trace Color	Trace Name	Y1
	X Values	7.7050M
CURSOR 1,2	V(R8:2)/V(R9:1)	5.6028

Fig 2.4 Frequency response of inverting amplifier with case 1



Trace Color	Trace Name	Y1
	X Values	7.9865M
CURSOR 1,2	V(R8:2)/V(R9:1)	2.8298

Fig 2.5 Frequency response of inverting amplifier with case 2



Trace Color	Trace Name	Y1
	X Values	8.1635M
CURSOR 1,2	V(R8:2)/V(R9:1)	1.4184

Fig 2.6 Frequency response of inverting amplifier with case 3

2.4 CONCLUSION

In this chapter details about CFOA AD844, its functional and internal architecture are discussed. To derive the characteristics equations internal diagram is explained further. Since CFOA offers gain-bandwidth independence so an inverting amplifier is designed to prove the same. A basic knowledge of CFOA described here is used in designing First order, Second Order and Higher order Filters which will be discussed in further chapters.

CHAPTER 3

FIRST ORDER FILTERS REALIZATION

In the previous chapter the characteristics of the CFOA were presented in brief. In the present chapter we have used these characteristics to derive and implement first order transfer functions using AD844 type CFOAs. Filter is also called as one-pole filter. It is so called because it uses only one reactive element that is only one capacitor.

3.1 FIRST ORDER LOW PASS FILTER USING CFOA AD844

An active low pass filter is the combination of an active device, resistor, capacitor which basically intends to produce high attenuation above the certain frequency and little and almost negligible attenuation below that certain frequency. This certain frequency where transition occurs is called as cut off frequency or corner frequency. The RC circuit connected here will provide a low frequency path to the input of the amplifier. This configuration of low pass filter designed using CFOA instead of traditional VOA has an advantage that its gain does not remain fixed at unity gain. It can be varied by varying the feedback resistor value [16, 17].

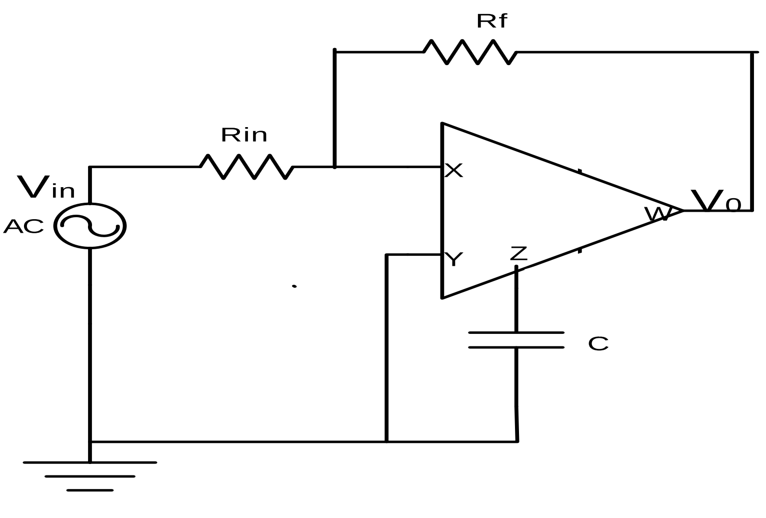


Fig 3.1 Circuit Diagram of First Order Low Pass Filter

Standard transfer function of a first order low pass filter is as follows

$$\frac{V_0}{V_{in}} = K\frac{\omega_0}{s+\omega_0} \tag{3.1}$$

Here K is the constant Dc gain and ω_0 is the cut-off frequency in radians

Since amplifier here is CFOA so $I_Z = I_X$

$$\frac{V_{in}-0}{R_{in}} + \frac{V_0-0}{R_f} = V_0\,(sC) \tag{3.2}$$

$$\frac{V_0}{V_{in}} = -\frac{R_f}{R_{in}}\frac{1}{sCR_f+1} \tag{3.3}$$

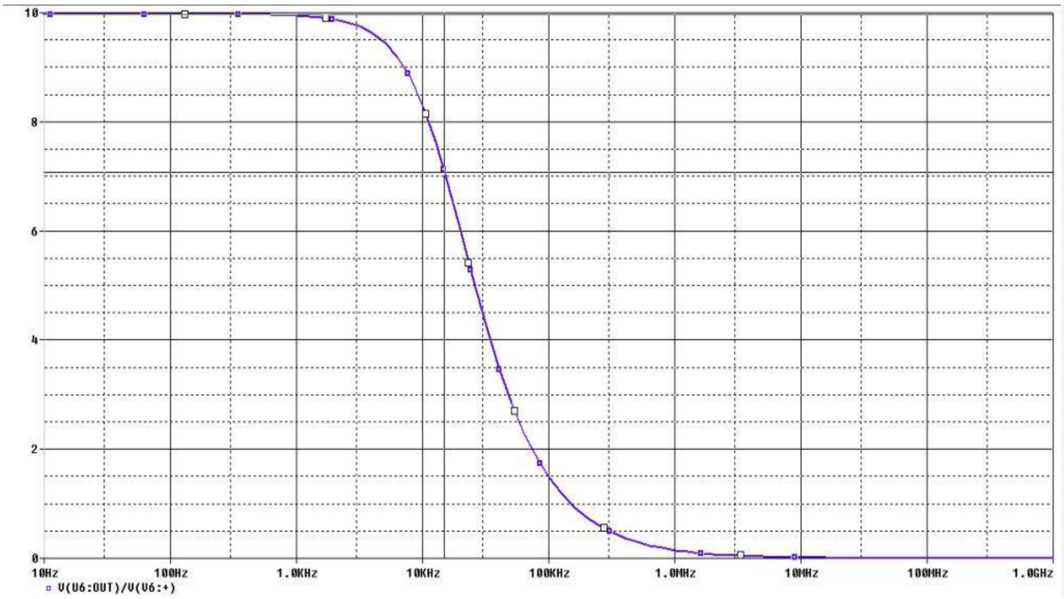
Here gain K is equal to ratio of feedback resistor and input resistor

$$K = \frac{R_f}{R_{in}} \tag{3.4}$$

And the cut off frequency in radians is equal to

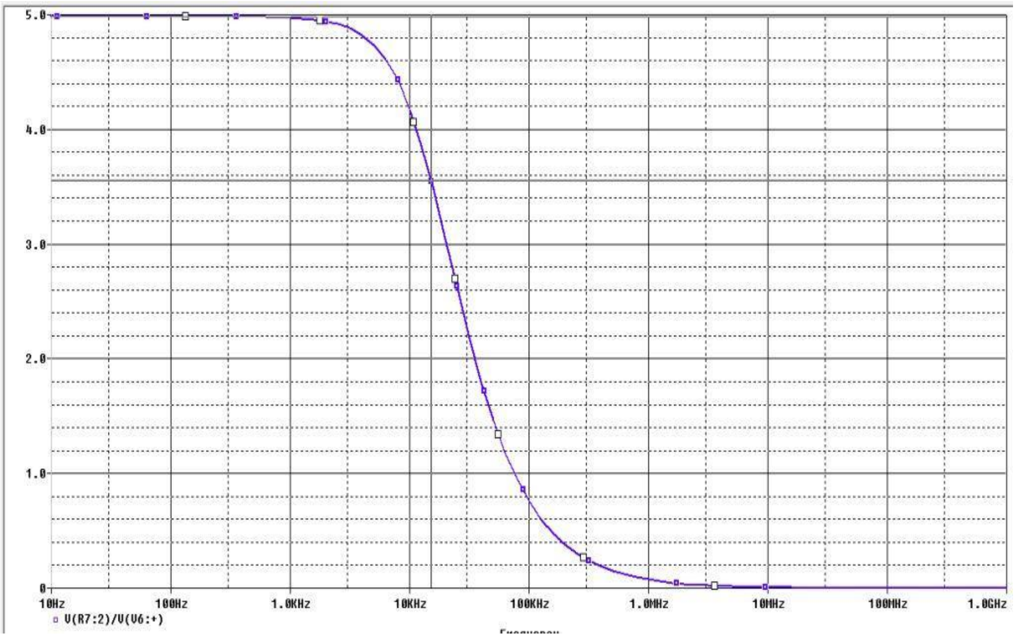
$$\omega_0 = \frac{1}{CR_f} \tag{3.5}$$

A low pass filter was designed with following component values $R_{in} = 1K\Omega$, $R_f = 10K\Omega$ and $C = 1nF$ to give a DC gain of 10 and a cut off frequency 0f 15.9 KHz. The transient response for an input voltage of 100mV pp at 1KHz is shown in Fig. 3.4.The frequency response of the circuit is given in Fig 3.2. Since the gain and bandwidth are independent in CFOA so with components values $R_{in} = 1K\Omega$, $R_f = 10K\Omega$ and $C = 1nF$ the dc gain of the circuit will become 5 but the cut off frequency will remains same. The frequency response of this circuit is given in Fig 3.3



Trace Color	Trace Name	Y1
	X Values	14.871K
CURSOR 1,2	V(U6:OUT)/V(V6:+)	7.0745

Fig 3.2 Simulated frequency response of first order low pass filter



Trace Color	Trace Name	Y1
	X Values	15.087K
CURSOR 1,2	V(R7:2)/V(V6:+)	3.5550

Fig 3.3 Simulated Frequency response of first order low pass filter with gain adjustment

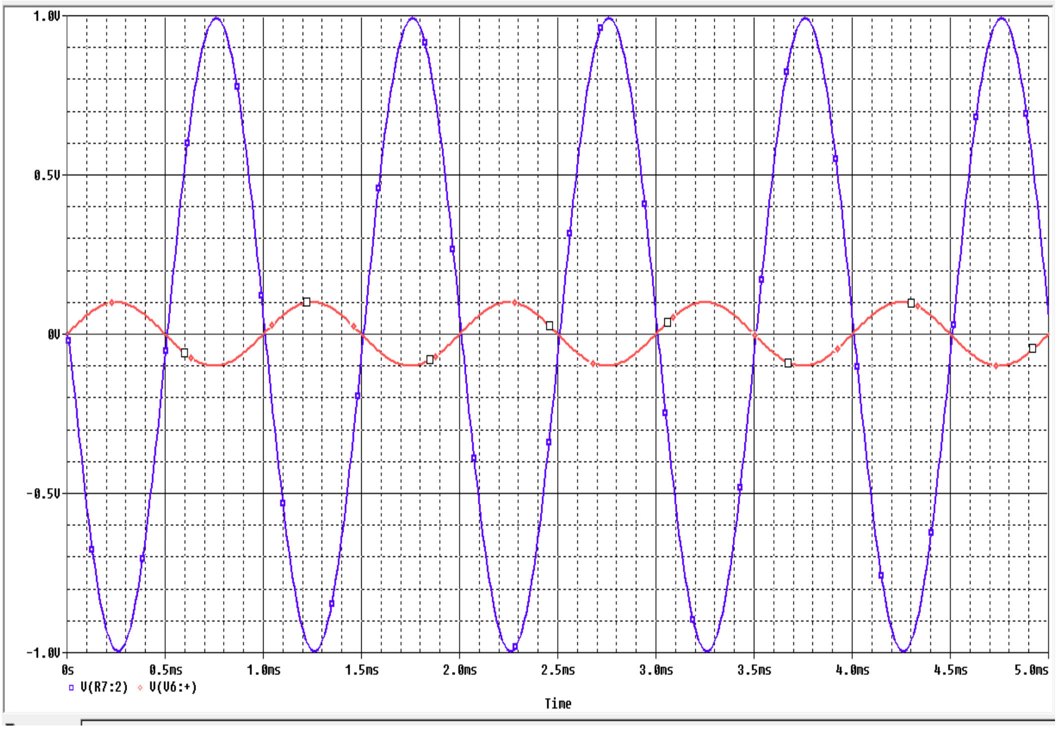


Fig. 3.4 Transient response of first order low pass filter

3.2 HIGH PASS FILTER USING CFOA AD844

An active high pass filter is the combination of the active devices, resistors and capacitors which initially produces high attenuation till a certain frequency and almost negligible attenuation after that certain frequency. This certain frequency where transition occurs is called as cut off or corner frequency. Filter designing decides the amount of attenuation exhibited by each frequency. Active high pass filter does not have infinite frequency response just like the passive filter. Maximum pass band frequency of the active high pass filter is limited by the open-loop characteristics or bandwidth of the operational amplifier being used. This gives them the look of band pass filter with high cut-off frequency. In traditional VOAs it is limited to gain bandwidth product but with CFOA gain can be changed and the bandwidth remains same [18,19].

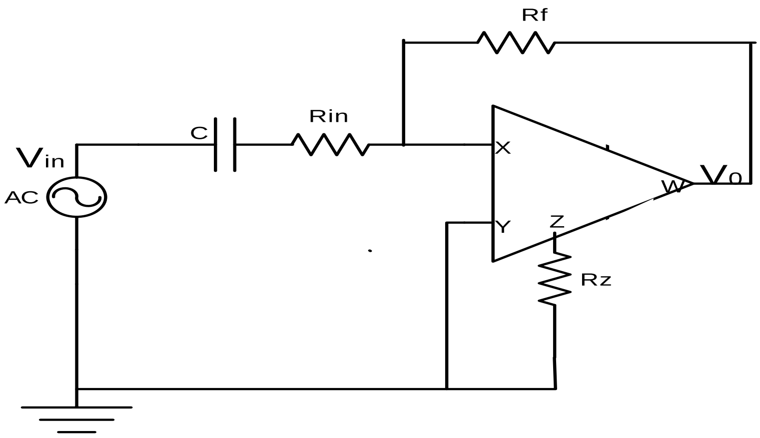


Fig 3.5 Circuit Diagram of First Order High Pass Filter

Standard transfer function of the first order High pass filter is given by

$$\frac{V_0}{V_{in}} = K\frac{s}{s+\omega_0} \tag{3.6}$$

Here K is the dc constant gain and ω_0 is the cut off frequency in radians

Since amplifier here is CFOA so $I_Z = I_X$

$$\frac{(V_{in}-0)sC}{scR_{in}+1} + \frac{V_0 - 0}{R_f} = \frac{V_0}{R_z} \tag{3.7}$$

Here R_f = R_z

$$\frac{V_0}{V_{in}} = -\frac{`1}{2}\frac{R_f}{R_{in}}\frac{sCR_{in}}{sCR_{in}+1} \tag{3.8}$$

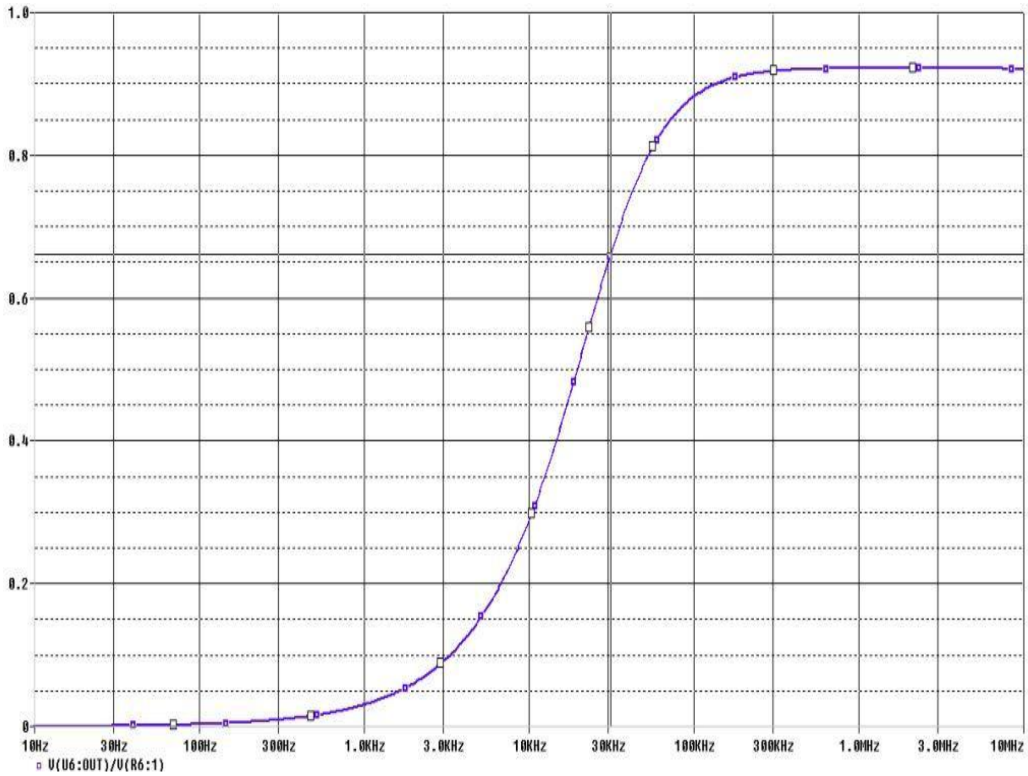
Here gain K is equal to ratio of feedback resistor and the input resistor

$$K = \frac{R_f}{R_{in}} \tag{3.9}$$

And the cut off frequency in radians is equal to

$$\omega_0 = \frac{1}{CR_f} \tag{3.10}$$

A high pass filter was designed with following component values $R_{in} = 0.5K\Omega$, $R_z = 1K\Omega$ and $R_f = 1K\Omega$ and $C = 0.01uF$ to give a DC gain of 1 and a cut off frequency of 31.8 KHz. The frequency response of the circuit is given in Fig 3.6.



Trace Color	Trace Name	Y1
	X Values	31.224K
CURSOR 1,2	V(U6:OUT)/V(R6:1)	661.348m

Fig 3.6 Frequency response of first order high pass filter

3.3 ALL PASS FILTER USING CFOA AD844

An all pass filter passes all the frequency components of the input signal without any attenuation but it provides some phase shift in the output signal for different frequencies of the input signal. A first order all pass filters has a zero on the positive real axis and a pole on the negative real axis. They are the mirror images of each other. Since they provide phase shift so they can be used as phase shifters in the circuits which require phase shaping [20, 21].

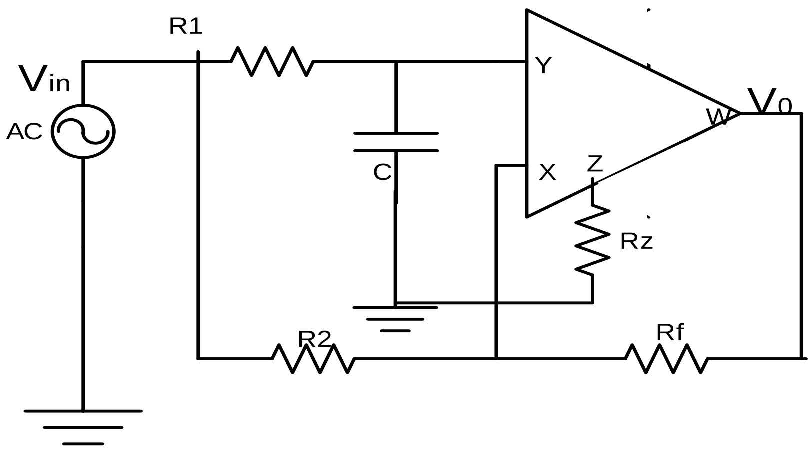


Fig 3.7 Circuit Diagram of First Order All Pass Filter

Since amplifier here is CFOA so $I_Z = I_X$

$$\frac{(V_{in}-0)}{R_{in}} + (V_{in} - 0)sC + (V_0 - 0)sC = \frac{(0-V_0)}{R_f} \tag{3.11}$$

$$\frac{V_0}{V_{in}} = -\frac{R_f}{R_{in}} \frac{sCR_{in} + 1}{sCR_f + 1} \tag{3.12}$$

Here the dc constant gain k is given by

$$K = \frac{R_f}{R_{in}} \tag{3.13}$$

Gain in db is given by

$$\text{K (db)} = 20\ log_{10}\text{K} \tag{3.14}$$

A all pass filter was designed with following component values $R_1 = 1K\Omega$, $R_2 = 1K\Omega$ and $R_f = 1K\Omega$ and $R_f = 10K\Omega$ and $C = 1nF$ to give a DC gain of 0.9 and a cut off frequency of 15.9KHz. The transient response for an input voltage of 100mV pp at 1 KHz is shown in Fig. 3.8. The frequency response of the circuit is given in Fig 3.9

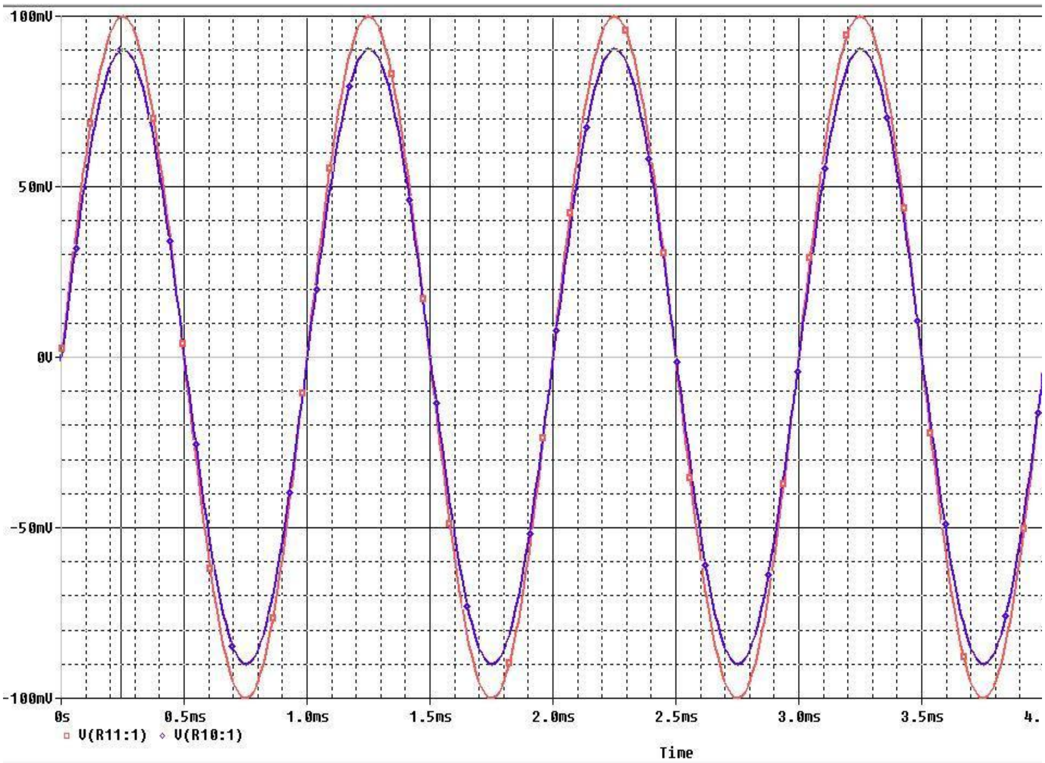
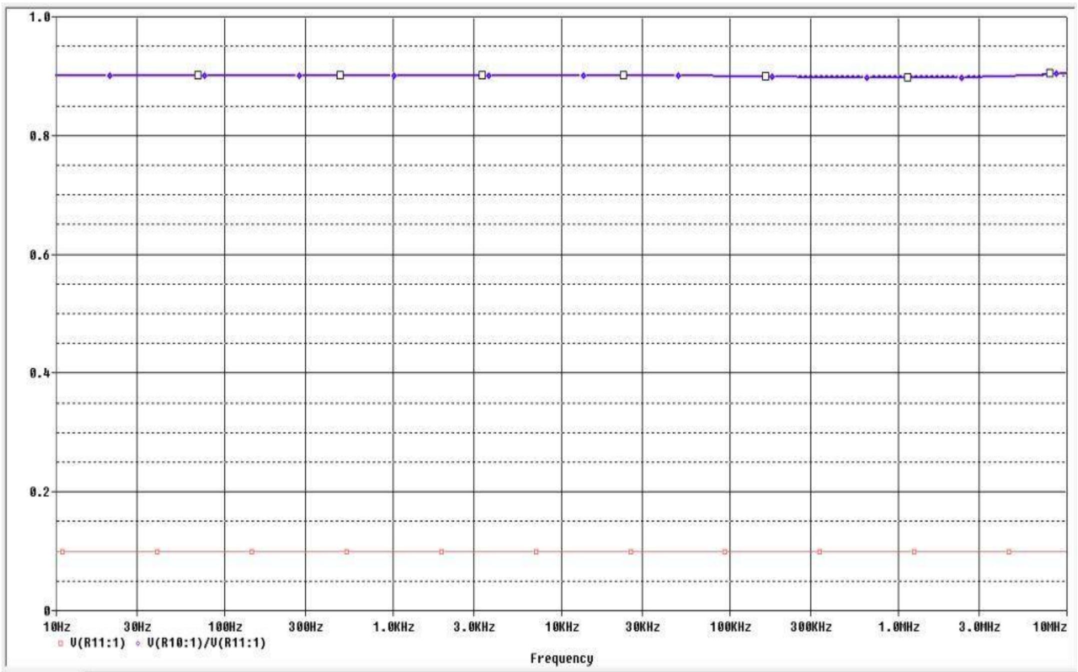
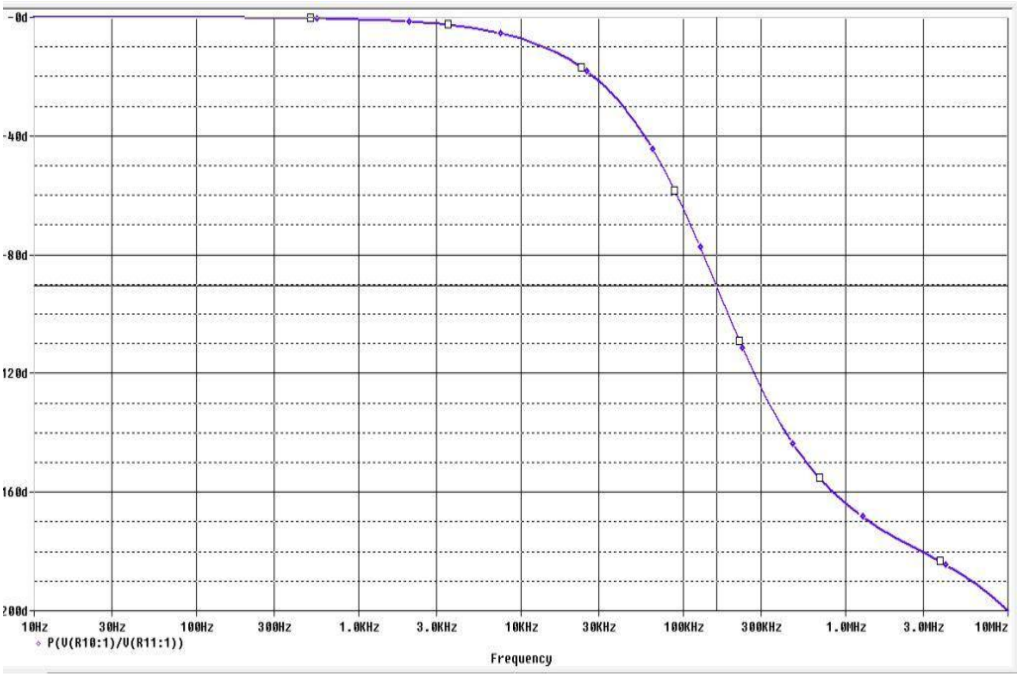


Fig. 3.8 Simulated Transient response of a first order all pass filter



Trace Color	Trace Name	Y1
	X Values	777.365
CURSOR 1,2	V(R11:1)	100.000m
	V(R10:1)/V(R11:1)	900.797m

Fig.3.9 Simulated Frequency response of an first order all pass filte



Trace Color	Trace Name	Y1
	X Values	159.698K
CURSOR 1,2	P(V(R10:1)/V(R11:1))	-90.426

Fig. 3.10 Simulated Phase response of a first order all pass filter

3.4 BILINEAR TRANSFER FUNCTION IMPLEMENTED USING CFOA AD844

In first order bilinear transfer function the number of poles are equal to the number of zeroes. There can be three possible cases with location of zero in s plane either it can be on left of jω axis or on jω axis or on the right of jω axis but here we are considering the first case for implementation. The first order bilinear transfer is given by [6].

$$T(s) = \frac{N(S)}{D(s)} = \frac{b_1 s + b_0}{a_1 s + a_0} \tag{3.15}$$

The coefficient of s here are real constants. Since there are three possible location of zero so coefficient b_i of numerator can be positive negative or zero but the coefficient a_i of the denominator should always be nonnegative for stability. This transfer function is called as bilinear because it have two straight lines equations in ratio. We can write above equation in the form of standard notation as follows.

$$T(s) = \frac{N(S)}{D(s)} = k\frac{s + z_1}{s + p_1} \tag{3.16}$$

Here $z_1 = \frac{b_0}{b_1}$ and $p_1 = \frac{a_0}{a_1}$

Ideal graph characteristics of the bilinear function is shown as follows

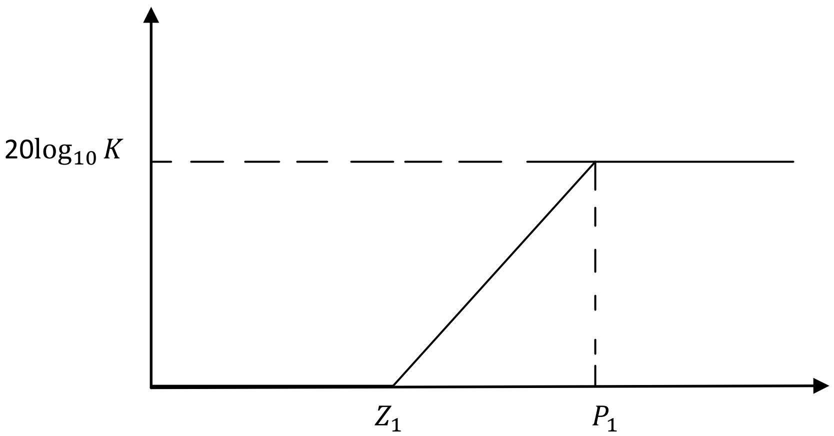


Fig 3.11 Ideal Characteristics of Bilinear Transfer Function with $Z_1 > P_1$

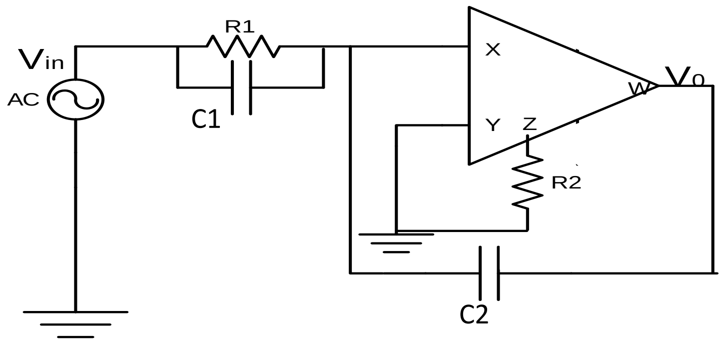


Fig 3.12 Circuit diagram implementing bilinear transfer function

Since amplifier here is CFOA so $I_Z = I_X$

$$\frac{(V_{in} - 0)}{R_{in}} + (V_{in} - 0)sC + (V_0 - 0)sC = \frac{(0 - V_0)}{R_f} \tag{3.17}$$

$$\frac{V_0}{V_{in}} = -\frac{R_f}{R_{in}}\frac{sCR_{in} + 1}{sCR_f + 1} \tag{3.18}$$

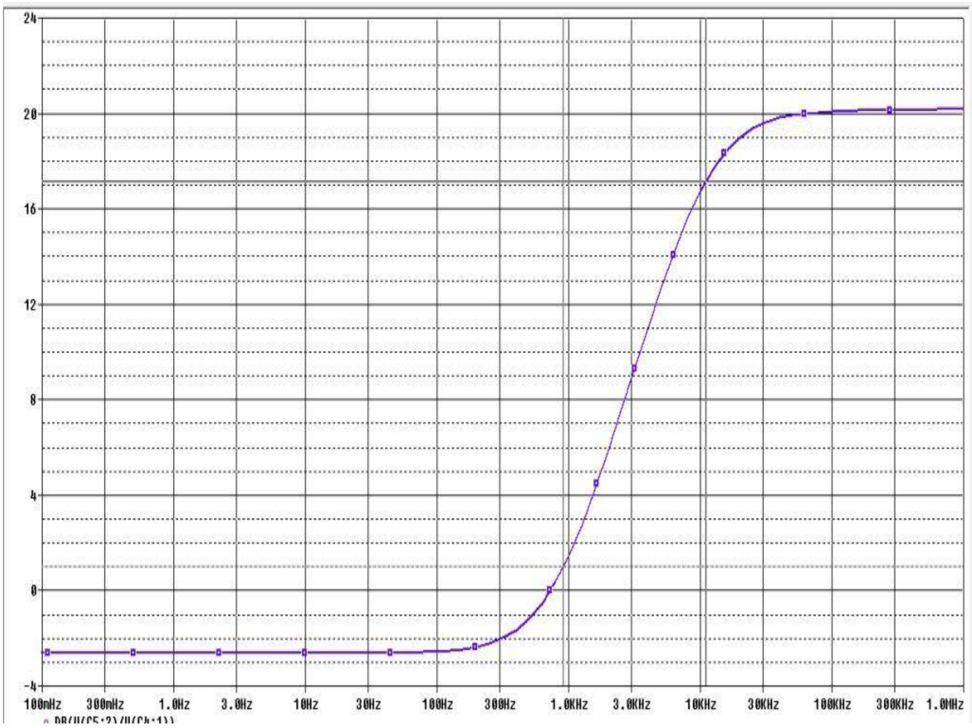
Here the dc constant gain k is given by

$$K = \frac{R_f}{R_{in}} \tag{3.19}$$

Gain in db is given by

$$K\ (db) = 20\ log_{10}K \qquad (3.20)$$

A bilinear transfer function was designed with following component values $R_1 = 4K\Omega$, $R_2 = 3K\Omega$ and $C_1 = 50nF$ and $C_2 = 4nF$ to give a DC gain of 0.9 and a cut off frequency of 15.9KHz.. The frequency response of the circuit is given in Fig 3.13.



Trace Color	Trace Name	Y1	Y2
	X Values	11.003K	910.448
CURSOR 1,2	DB(V(C5:2)/V(C4:1))	17.149	1.0142

Fig 3.13 Frequency response of implemented bilinear transfer function

3.5 CONCLUSION

This chapter is dedicated to the several first order filters function that are realized using CFOA AD844. First order low pass, high pass and all pass filters are designed using their standard transfer function and characteristics of CFOA. Also a Bilinear function is implemented by using the characteristics of CFOA and standard notation for bilinear transfer function.

CHAPTER 4

SECOND ORDER FILTER REALIZATION

Second order filter are also called as biquads. They are most useful in the field of analog signal processing requirements. Sections of them can be used for configuring universal filters. Also the cascade connection of these biquads can be used to design higher order filters. The second order filters can be designed using a single ABB(Sallen-key, Butterworth, Chebyshev, Bessel etc.) or more than one ABB(Two –integrators in a loop, GIC based etc.). In this chapter we have designed both type of Biquads using AD844 type CFOAs.

There are two main designing parameters of the second order filter namely $\omega_0$and Q where ω_0 is the -3db cut off frequency in radians and Q is the quality factor of the poles. To define these parameters let us consider the two poles of the second order filter in s-plane be $-\alpha \pm j\beta$. So now the denominator of the second order fiter will be like [13].

$$D(s) = s^2 + 2\alpha s + \alpha^2 + \beta^2 \tag{4.1}$$

Standard equation of denominator of a second order filter is given by

$$D(s) = s^2 + \frac{\omega_0}{Q} s + {\omega_0}^2 \tag{4.2}$$

By comparing both the equations we get

$$Q = \frac{\omega_0}{2\alpha} \tag{4.3}$$

$${\omega_0}^2 = \alpha^2 + \beta^2 \tag{4.4}$$

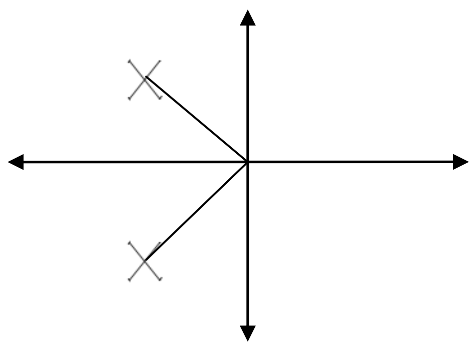


Fig 4.1 Pole locations of second order transfer function.

For the maximally flat response Q should be equal to 0.707.

4.1 SALLEN-KEY BIQUAD USING CFOA AD844

It was the first active filter which came into theories. It is most common topology of designing single amplifier based second order filter. The generalized circuit of Sallen-key is shown below. According to components used in places of impedances we can classify the configuration as low pass and high pass. In the given below configuration the impedances chosen decides the type of filter we want to design either low or high [6].

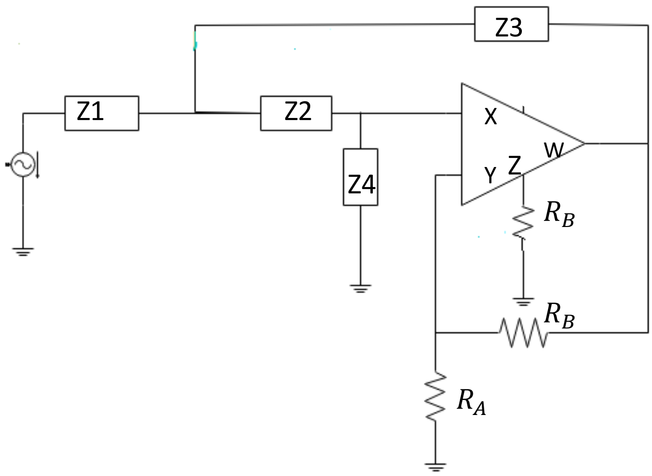


Fig 4.2 Circuit diagram of SALLEN-KEY configuration

4.1.1 SALLEN-KEY LOW PASS FILTER

The specifications of the Sallen and key low pass filter are same as that of the general second order low pass filter only the configuration of both differs from each other. Standard transfer function of a second order low pass filter is given as follows.

$$\frac{V_0}{V_{in}} = \frac{K\omega_0^2}{s^2 + \frac{\omega_0}{Q}S + \omega_0^2} \tag{4.5}$$

Here K refers to the dc constant gain, ω_0 refers to -3Db down cut off frequency in radians and Q is the Q-factor which represents the flatness of the curve. Now according to the above standard diagram of Sallen-key Biquads for low pass filter Z_1 and Z_2 are resistors while Z_3 and Z_4 are capacitors.

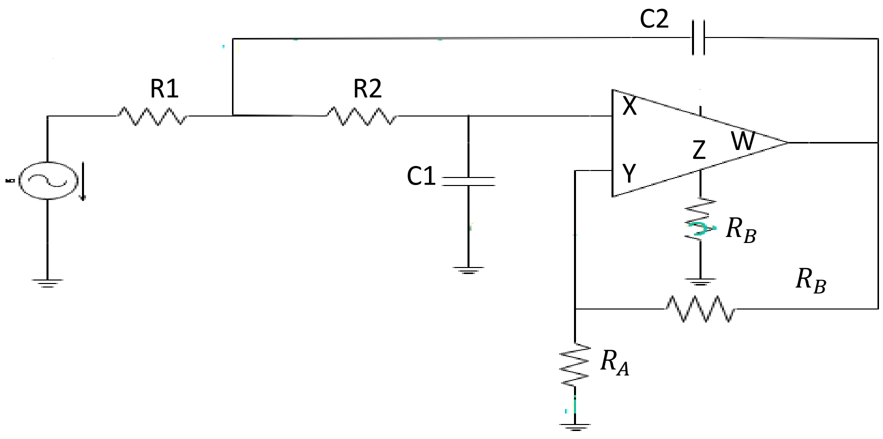


Fig. 4.3 Circuit diagram of SALLEN-KEY low pass filter

According to the characteristics equation of the CFOA that is $I_X = I_Z$ and $I_Y = 0$ we can write the following equation

$$V_0 = \frac{1}{2}\left[1 + \frac{R_B}{R_A}\right] V_X \tag{4.6}$$

$$V_{in}G_1 = V(sC_1 + G_1 + G_2) - sC_1V_0 - G_2V_X \tag{4.7}$$

$$V_X(sC_2 + G_2) = G_2V \tag{4.8}$$

Here V is the node voltage as shown in fig. So the final transfer function of the circuit determined using these equations is

$$\frac{V_0}{V_{in}} = \frac{KG_2G_1}{s^2C_1C_2 + S[C_2(G_1 + G_2) + C_1G_2\{1 - K\}] + G_1G_2} \tag{4.9}$$

Here

$$K = \frac{1}{2}\left[1 + \frac{R_B}{R_A}\right] \tag{4.10}$$

$$\omega_0^2 = \frac{G_2G_1}{C_1C_2} \tag{4.11}$$

$$Q = \frac{\sqrt{G_2G_1}}{G_1 + G_2(2 - K)} \tag{4.12}$$

Keeping Q-factor fix to 0.707 for the maximally flat response and using the above written equations we can determine the components values, gain and then the cut-off frequency of the circuit. If we keep $R_1 = R_2 = R$ and $C_1 = C_2 = C$ then

$$Q = \frac{1}{3 - K} \tag{4.13}$$

So the elements values to be used can be determined by following equation

$$R = \frac{1}{\omega_0 C}, \qquad R_B = \left(5 - \frac{2}{Q}\right) R_A \tag{4.14}$$

A low pass filter was designed with following component values $R_1 = 2K\Omega$, $R_2 = 2K\Omega$ and $R_A = 1K\Omega$ and $R_B = 2.16K\Omega$ and $C_1 = 1nF$ and $C_2 = 1nF$ to give a DC gain of 1.58 and a cut off frequency of 79KHz. The transient response for an input voltage of 100mV pp at 1 KHz is shown in Fig. 4.4. The frequency response of the circuit is given in Fig 4.5.

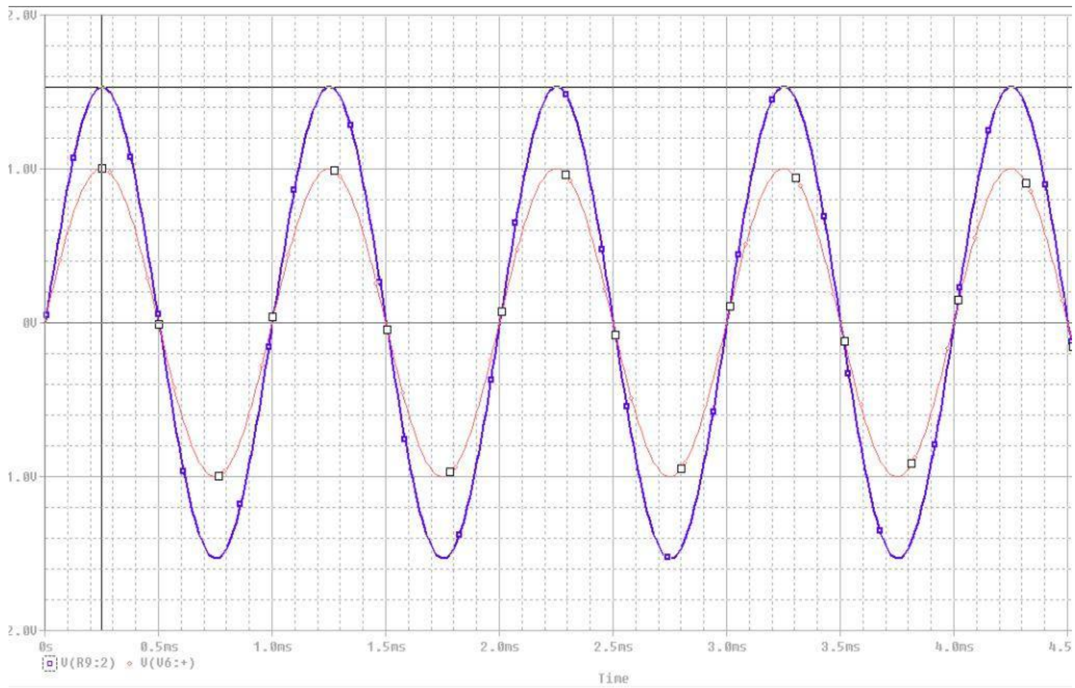
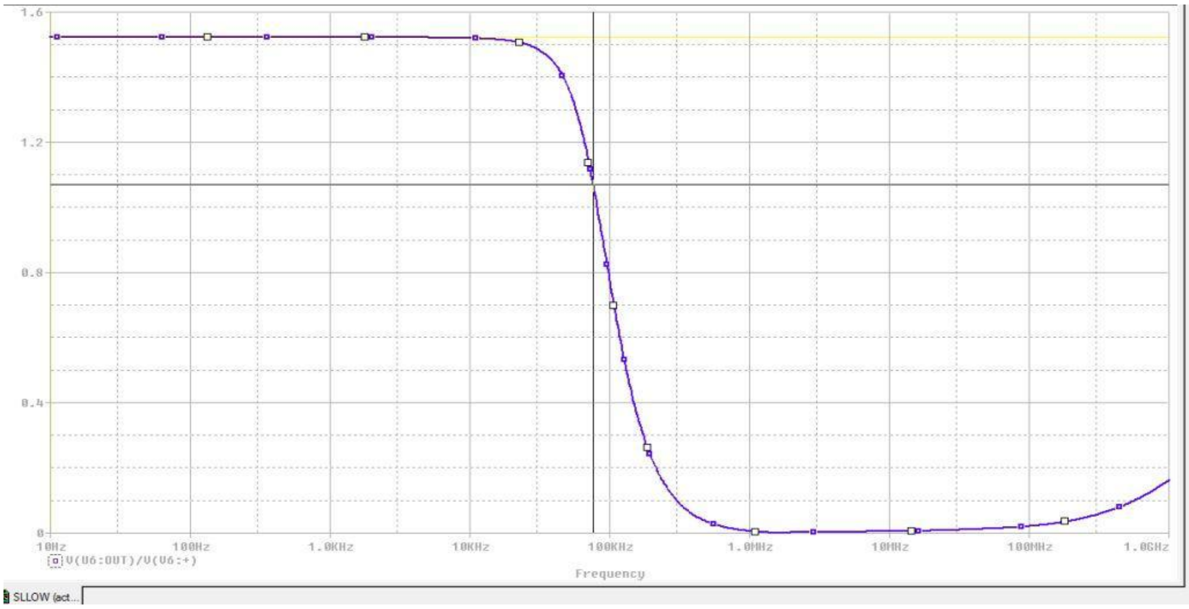


Fig. 4.4 Transient response of SALLEN-KEY low pass filter



Trace Color	Trace Name	Y1
	X Values	76.021K
CURSOR 1,2	V(U6:OUT)/V(V6:+)	1.0703

Fig 4.5 Frequency response of SALLEN-KEY low pass filter

Gain Adjustment In Sallen-Key type filter.

Sallen-key has a limitation that its gain is fixed at K= $3-\frac{1}{Q}$. So to adjust the gain of the biquads a voltage divider circuit is introduced but poles does not have any effect due to addition of the circuit. Resistor R_1 is replaced by a Voltage Divider circuit consisting of

$$R_x = \frac{R_1}{a}, \quad R_y = \frac{R_1}{1-a} \tag{4.15}$$

Here a should be less than 1. Let $a = 0.5$. According to this the value of $R_x = 4K\Omega = R_y$. Now the gain of the circuit becomes H= Ka

The circuit diagram with gain adjustment is shown below along with output gain result which is equal to 0.79 and there is no effect on the cut off frequency of the circuit. It will remain same.

C2

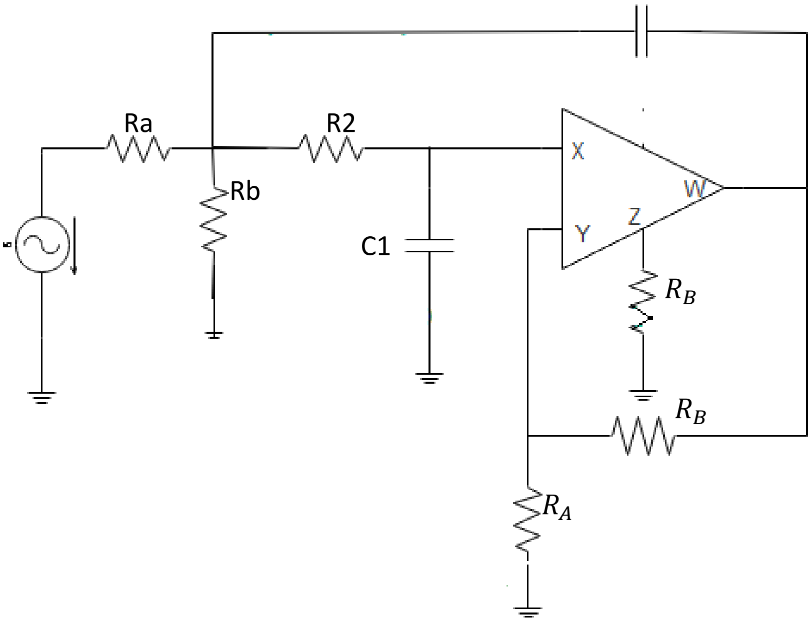
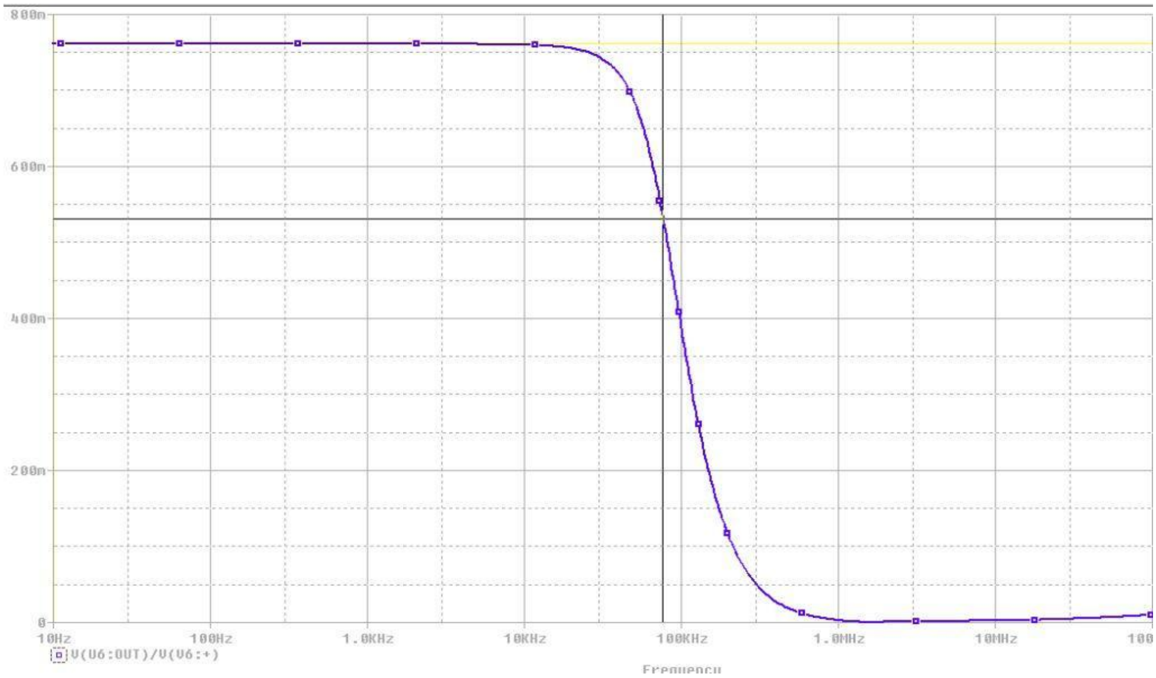


Fig 4.6 Circuit diagram of SALLEN-KEY low pass filter with gain adjustment



Trace Color	Trace Name	Y1
	X Values	76.648K
CURSOR 1,2	V(U6:OUT)/V(V6:+)	531.035m

Fig 4.7 Frequency response of SALLEN-KEY low pass filter with gain adjustment

4.1.2 SALLEN KEY HIGH PASS FILTER

Characteristics of the Sallen-key high pass filter are just like the general second order high pass filter except their configuration. Their designing parts differ from each other. A general second order transfer function is given as follows

$$\frac{V_0}{V_{in}} = \frac{KS^2}{s^2 + \frac{\omega_0}{Q}S + \omega_0^2} \tag{4.16}$$

Here K is the DC constant gain and ω_0 is the -3db down cut off frequency in radians and Q is called Q-factor of the curve. High pass filter just exchanges the components which were used in the Sallen-key low pass filter. So now Z_1 and Z_2 are capacitors and Z_3 and Z_4 are resistors [6].

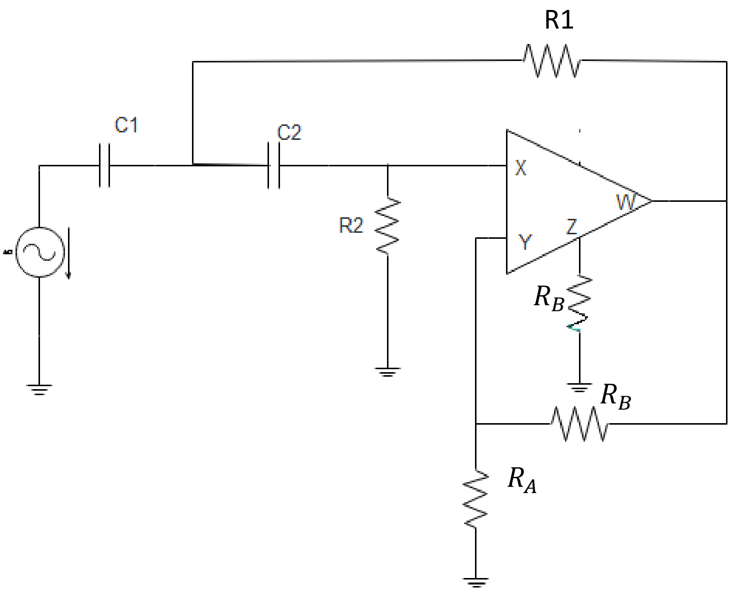
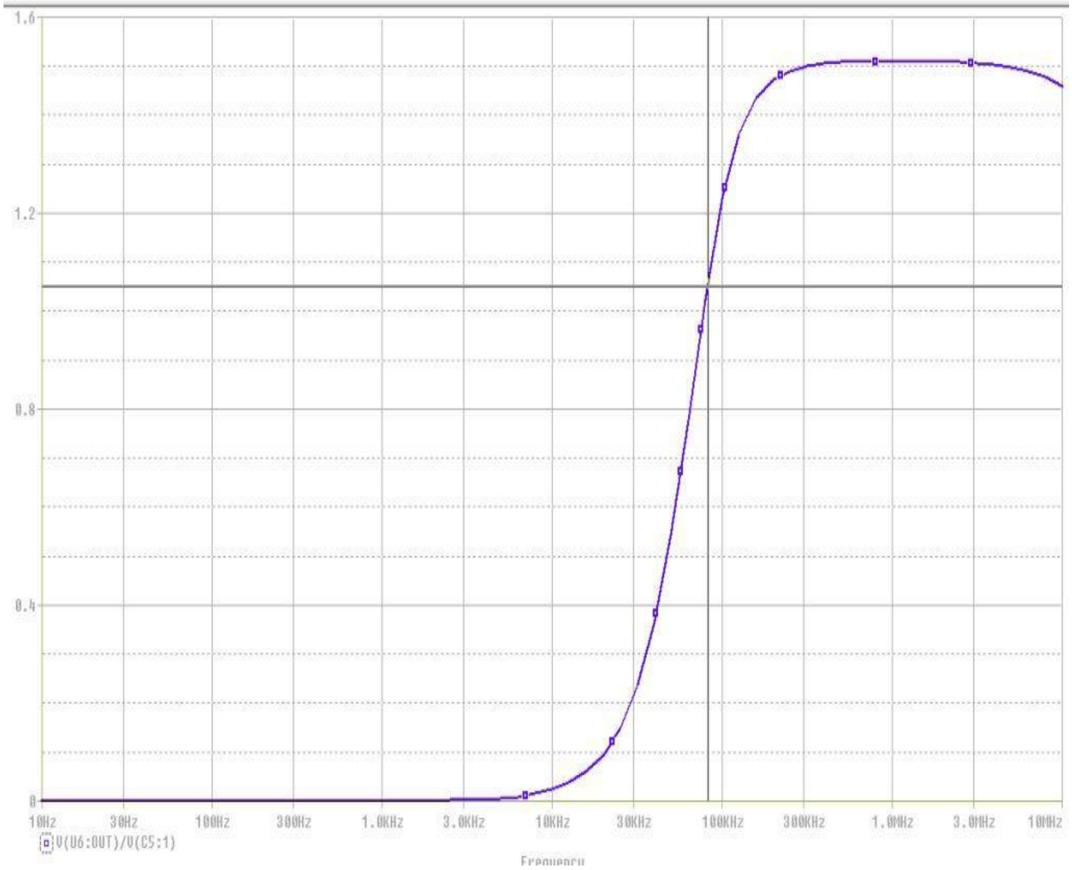


Fig. 4.8 Circuit diagram of SALLEN-KEY high pass filter

Everything is similar to the low pass filter including the gain and the cut-off frequency except the square of s term will be there in numerator. The transfer function of the Sallen-key high pass filter is given as below

$$\frac{V_0}{V_{in}} = \frac{Ks^2G_2G_1}{s^2C_1C_2 + s[C_2(G_1 + G_2) + C_1G_2\{1 - K\}] + G_1G_2} \tag{4.17}$$

A high pass filter was designed with following component values $R_1 = 2K\Omega$, $R_2 = 2K\Omega$ and $R_A = 1K\Omega$ and $R_B = 2.16K\Omega$ and $C_1 = 1nF$ and $C_2 = 1nF$ to give a DC gain of 1.58 and a cut off frequency of 79KHz. The transient response for an input voltage of 100mV pp at 1 KHz is shown in Fig. 4.3. The frequency response of the circuit is given in Fig 4.9



Trace Color	Trace Name	Y1
	X Values	81.833K
CURSOR 1,2	V(U6:OUT)/V(C5:1)	1.0510

Fig 4.9 Frequency response of SALLEN-KEY high pass filter

4.2 TWO INTEGRATORS IN A LOOP TYPE BIQUAD USING CFOA

It is a second order filter which is designed using integrators which are connected in cascade. Its most popular implementations are KHN and the Tow

Thomas Biquad. We can realize three basic filters output through KHN biquad configuration which are High Pass, Low Pass, and Band pass. Using Tow Thomas configuration on the other hand a Low Pass, Band Pass and inverting Low Pass can be realized. For designing let us take ω_0=1.Transfer function of the standard low pass filter is given by [23]

$$\frac{V_L}{V_{in}} = \frac{K}{s^2 + \frac{\omega_0}{Q}s + 1} \tag{4.18}$$

Here the gain of the circuit is K and cut off is 1.Now let us manipulate the above equation to get the further equations.

$$sV_L = -\frac{1}{s + {}^1/_Q}(HV_{in} + V_L) = V_B \tag{4.19}$$

i.e.

$$V_L = \frac{1}{S}V_B \tag{4.20}$$

$$SV_B = -\left(HV_{in} + V_L + \frac{1}{Q}V_B\right) = -V_H \tag{4.21}$$

i.e.

$$V_B = -\frac{1}{S}V_H \tag{4.22}$$

Using the above equations we can draw the block diagram of the two-integrating loop as shown below

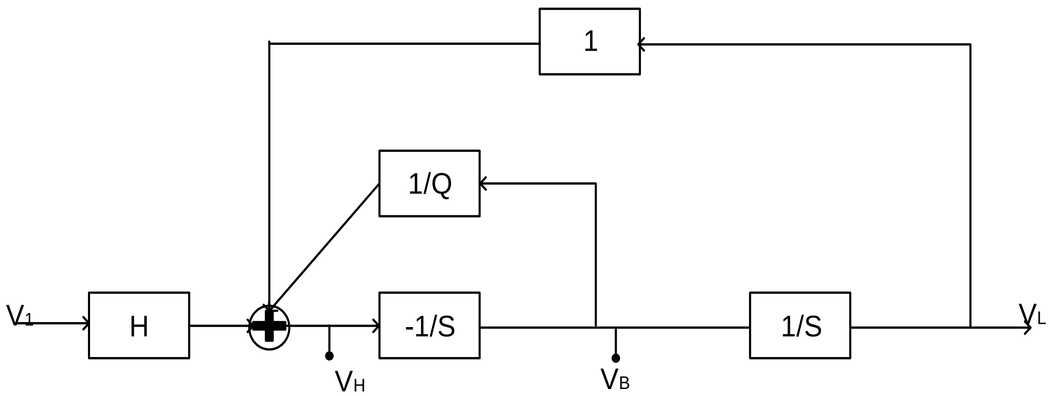


Fig. 4.10 Block diagram of Two Integrators in a Loop Biquad.[24]

So the block diagram realizes three nodes which realize three transfer functions which include low pass, high and bandpass functions are given as follows

$$\frac{V_L}{V_{in}} = -\frac{H}{s^2 + \frac{\omega_0}{Q}s + 1} = T_L(S) \tag{4.23}$$

$$\frac{V_B}{V_{in}} = -\frac{HS}{s^2 + \frac{\omega_0}{Q}s + 1} = T_B(S) \tag{4.24}$$

$$\frac{V_H}{V_{in}} = \frac{HS^2}{s^2 + \frac{\omega_0}{Q}s + 1} = T_H(S) \tag{4.25}$$

Gain of the low pass circuit is H while gain of the high pass and band pass circuit is HQ. Now to implement this block diagram three different circuit modules are considered. These circuit modules are designed using CFOA. The Tow-Thomas Biquad [25] is a circuit implementation of the block diagram shown in Fig 4.10 with a little modification: The summer and the first inverting integrator are combined into a single block. This results into one of the output V_H disappearing, but one additional inverting low pass filter output is now available. The CFOA based Tow-Thomas Biquad circuit is given below in Fig. 4.11.

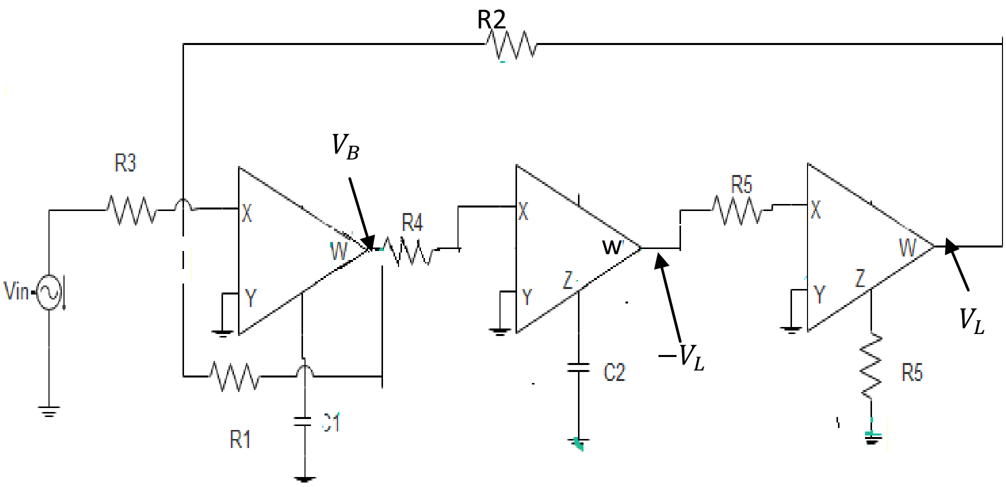


Fig. 4.11 Circuit diagram of Tow Thomas Biquad.

The transfer function of both low pass filter and band pass filter obtained using the above circuit is given as

$$\frac{V_L}{V_{in}} = T_L(s) = \frac{\frac{R_2}{R_3}\frac{1}{R_2R_4C_1C_2}}{s^2 + \frac{s}{R_1C_1} + \frac{1}{R_2R_4C_1C_2}} \quad (4.26)$$

$$\frac{V_B}{V_{in}} = T_B(s) = \frac{\frac{R_1}{R_3}\frac{s}{R_1C_1}}{s^2 + \frac{s}{R_1C_1} + \frac{1}{R_2R_4C_1C_2}} \quad (4.27)$$

So here gain of low pass and band pass is given as

$$K_L = \frac{R_2}{R_3} and\ K_H = \frac{R_1}{R_3} \quad (4.28)$$

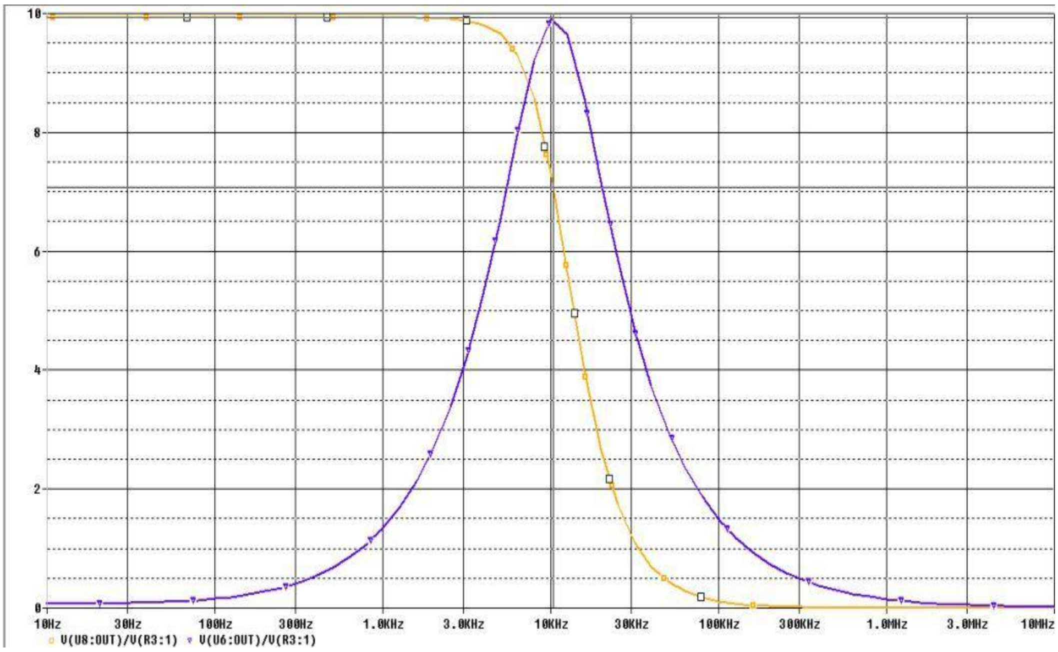
But the cut off frequency of low pass and the center frequency of band pass are identical and is given by

$$\omega_0^2 = \frac{1}{R_2R_4C_1C_2} \quad (4.29)$$

And the Q-factor of the circuit is given as

$$Q = \frac{R_1}{\sqrt{R_2R_4}}\sqrt{\frac{C_1}{C_2}} \quad (4.30)$$

The Tow Thomas Biquad was designed with the following components values $R_1 = 10K\Omega$, $R_2 = 10K\Omega$ and $R_3 = 1K\Omega$ and $R_4 = 20K\Omega$ and $R_5 = 1K\Omega$ and$C_1 = 1nF$ and $C_2 = 1nF$ to give a DC gain of 10 for both low pass and band pass filter and a cut off frequency of 10.36 KHz. The transient response of inverting low pass, low pass and band pass for an input voltage of 100mV pp at 1 KHz is shown in Fig. 4.13 and Fig 4.14 respectively. The frequency response of the circuit is given in Fig 4.12.



Trace Color	Trace Name	Y1
	X Values	10.360K
CURSOR 1,2	V(U8:OUT)/V(R3:1)	7.0745
	V(U6:OUT)/V(R3:1)	9.868

Fig. 4.12 Frequency response of Tow Thomas Biquad implementing band pass and low pass filter.

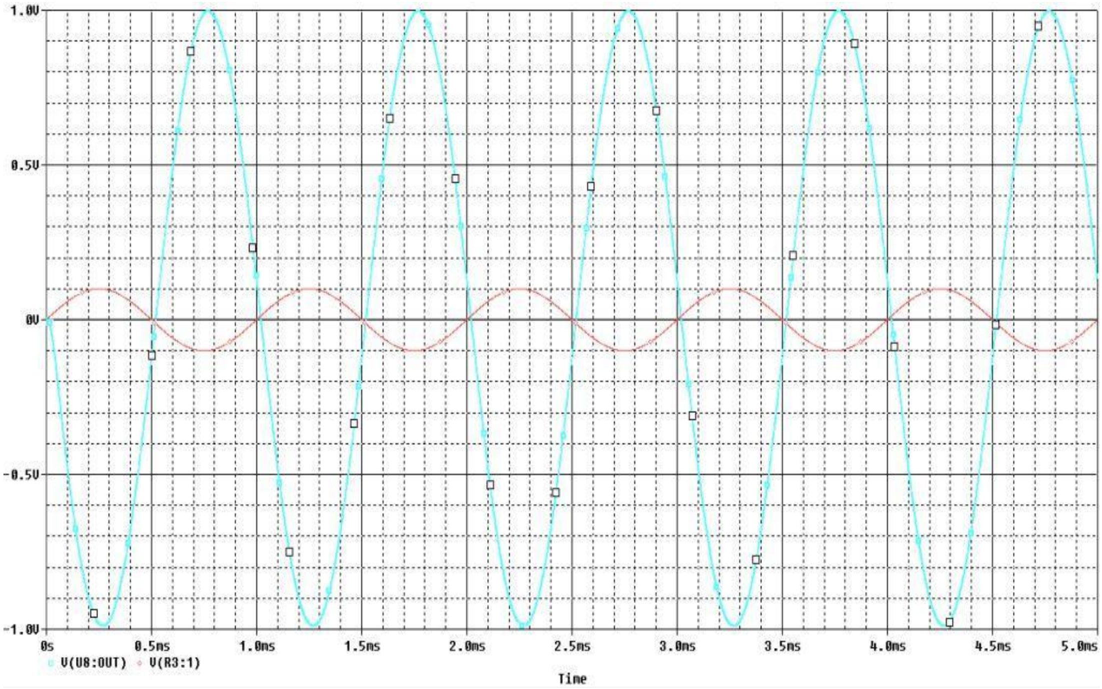
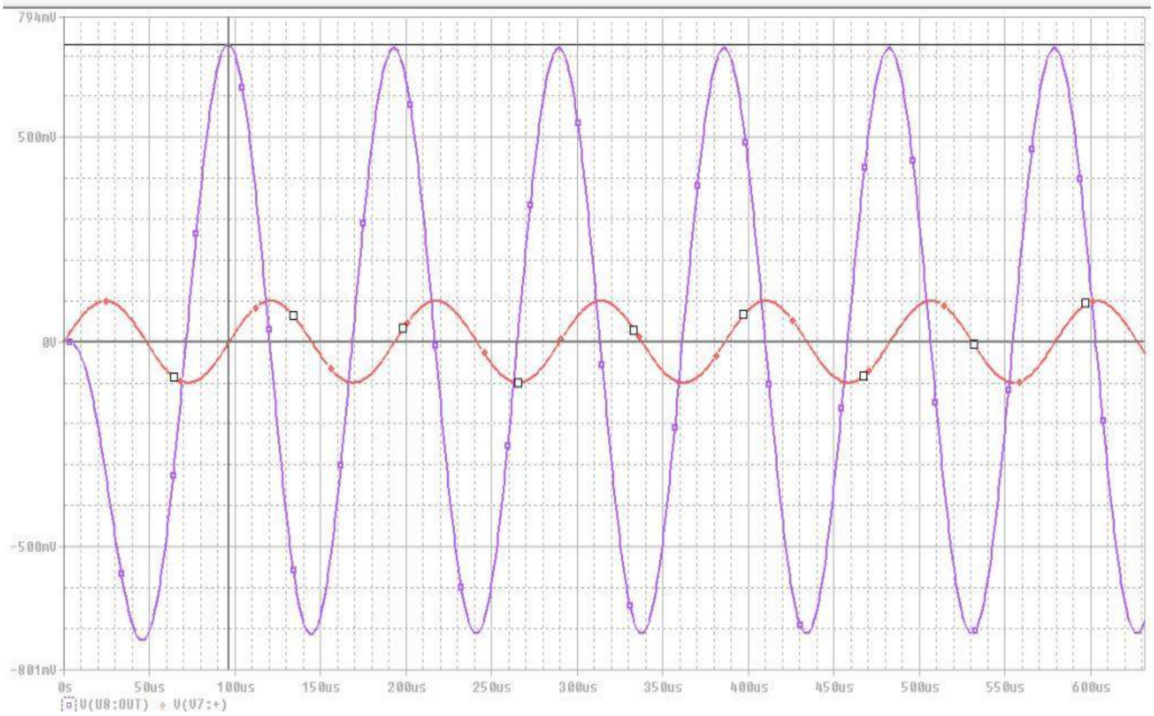


Fig 4.13 Transient response of Tow Thomas Biquad implementing inverting low pass filter.



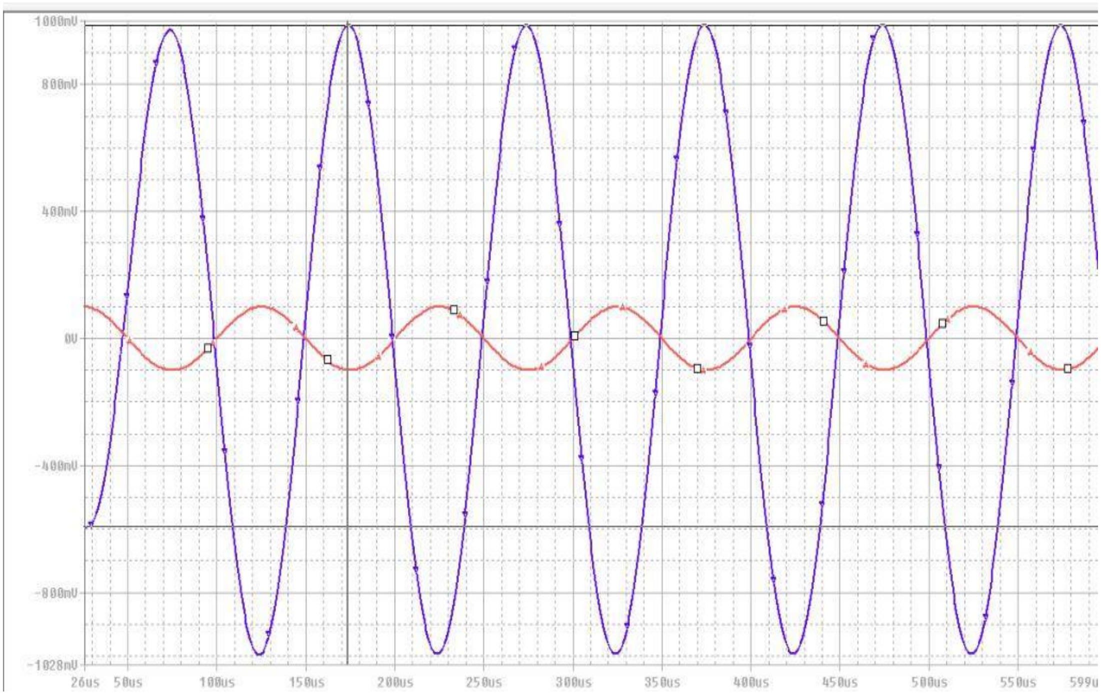


Fig 4.14 Transient response of Tow Thomas Biquad implementing band pass and low pass

4.3 GENRALIZED IMPEDANCE CONVERTER DERIVED BIQUAD USING CFOA

Generalized impedance converter (GIC) is two port network which can be used to realize simulated immittances that was proposed earlier. They were designed so that it can replace the frequency dependent elements such as Inductor from the circuit for active filter synthesis. They include elements such as resistors, capacitors and active elements. We can use these GICs in filters for replacing inductors. Now consider the following given circuit which simulates a grounded inductor.[25,26]

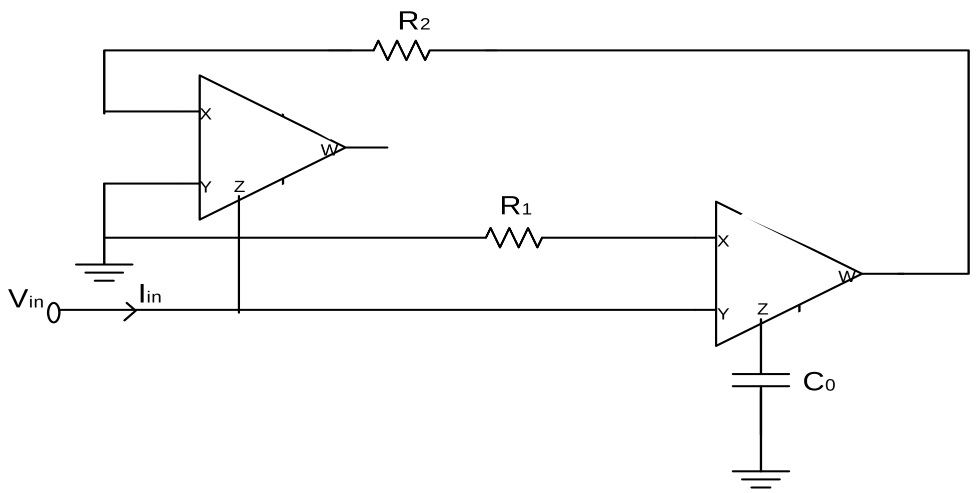


Fig. 4.15 Circuit diagram of grounded inductor

According to the characteristics of the CFOA we can write following two main equations from the circuit of GIC and they are as follows

$$V_1 = V_{Y2} = V_{X2} \tag{4.31}$$

$$\frac{0 - V_1}{R_1} = (0 - V_{W2})sC_0 \tag{4.32}$$

$$I_1 = I_{Z1} + I_{Y1} \text{ And } I_{Y1} = 0 \tag{4.33}$$

$$I_1 = I_{X1} = I_{Z1} \text{ And } V_{X1} = V_{YI} = 0 \tag{4.34}$$

$$I_1 = \frac{V_{W2} - V_{X1}}{R_2} \tag{4.35}$$

$$\frac{V_1}{I_1} = sC_0R_1R_2 \tag{4.36}$$

So here the value of L is determine by above equation and it is given as

$$L = C_0R_1R_2$$

Now we will replace the inductor in our passive circuit by this simulated grounded inductor to design a band pass and a high pass filter. Passive circuit considered for the Band Pass and High pass filter are shown as follows [27,28]

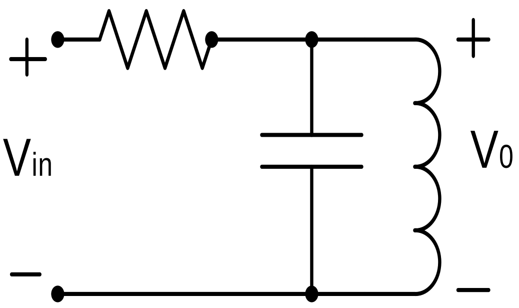


Fig. 4.16 Circuit diagram of Band pass filter

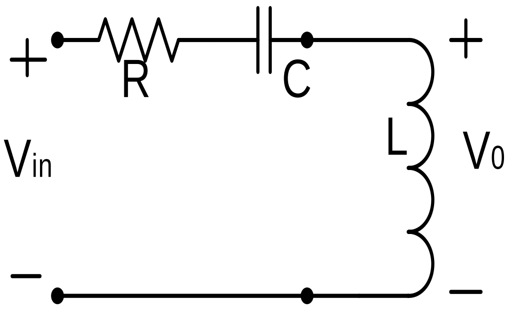


Fig. 4.17 Circuit Diagram of High pass filter

The transfer function of Band pass filters is given as follows

$$\frac{V_0}{V_{IN}} = \frac{s\frac{1}{RC}}{s^2 + \frac{1}{RC}s + \frac{1}{LC}} \tag{4.37}$$

While the transfer function of the High pass filter is given as follows

$$\frac{V_0}{V_{IN}} = \frac{s^2}{s^2 + \frac{R}{L}s + \frac{1}{LC}} \tag{4.38}$$

If we select $C_0 = 1nF, R_1 = 1K\Omega\ and\ R_2 = 1K\Omega$ then the value of the Simulated inductor is equal to 1mH. This inductor was used to replace the passive inductors used in Fig. 4.15 and 4.16. The resulting Band Pass and High Pass Filter are shown in Fig. 4.17 and 4.18. These filters were designed to have a cut-off frequency of 50.28 KHz, Q=0.707 and DC gain of 1 by selecting$C = 10nF,\ R = 200\ \Omega$ for Band Pass filter and selecting$C = 10nF,\ R = 500\Omega$ for High Pass Filter.

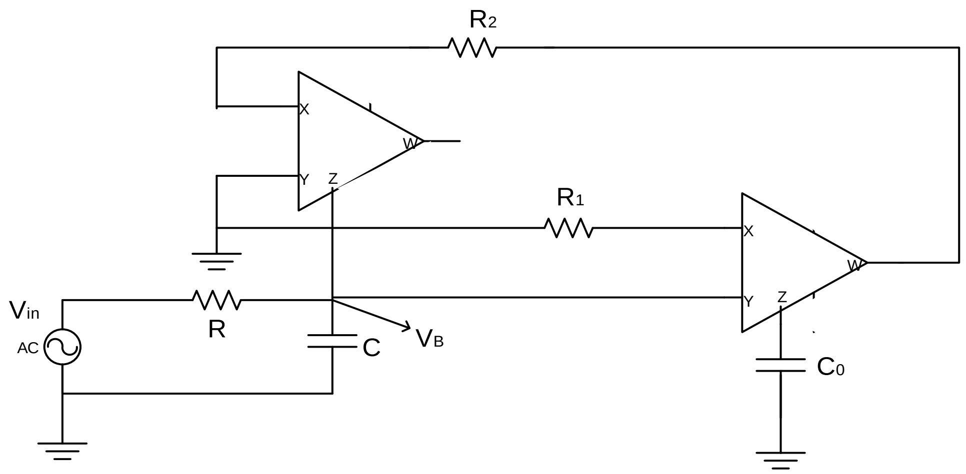


Fig. 4.18 Circuit diagram of band pass filter implemented using GIC.

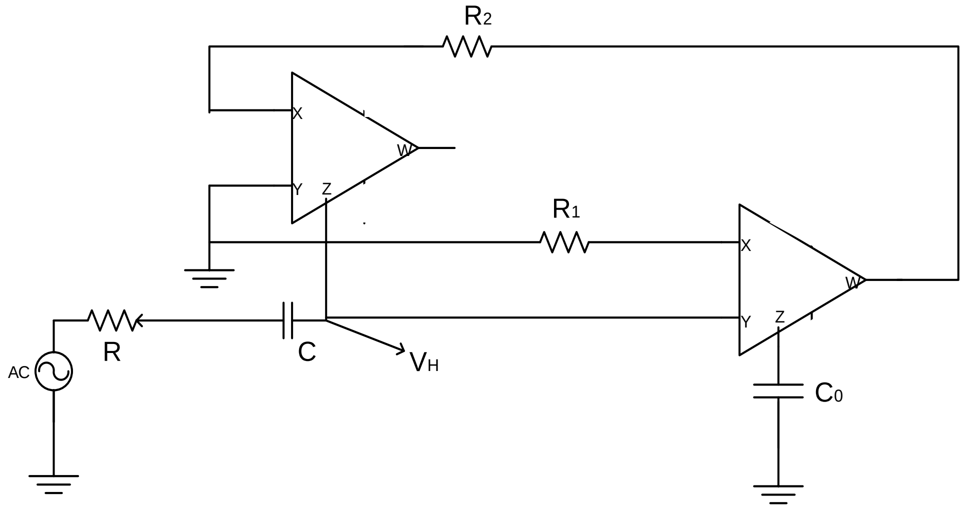
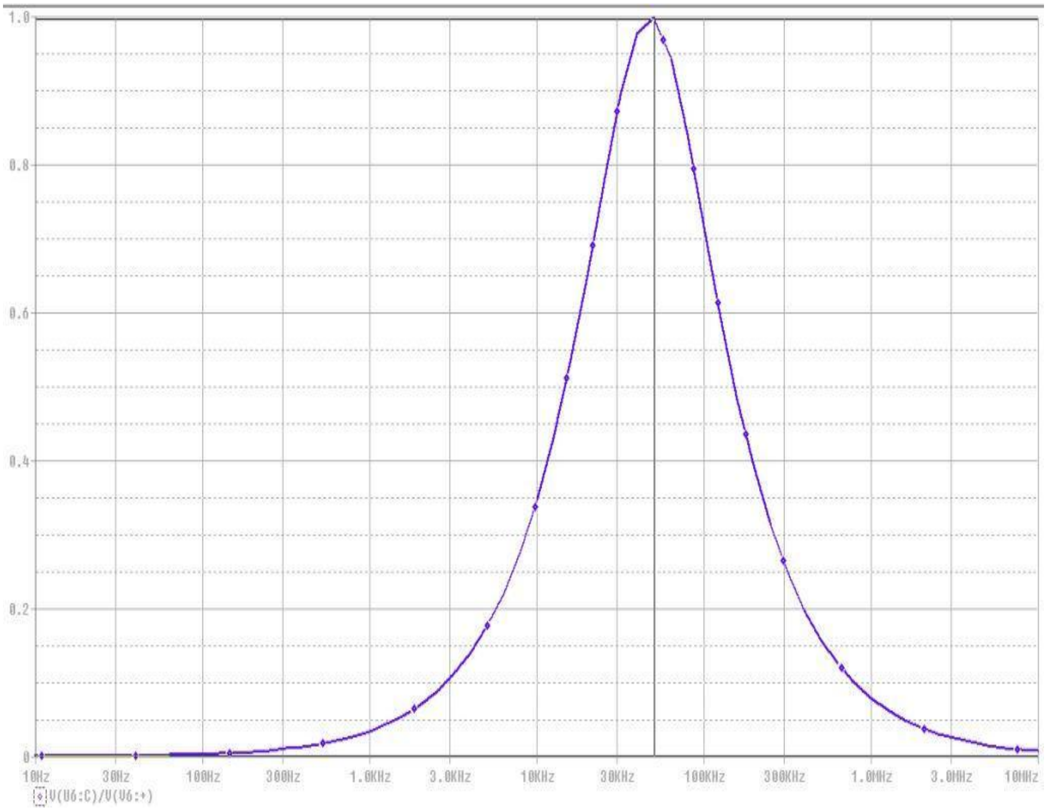


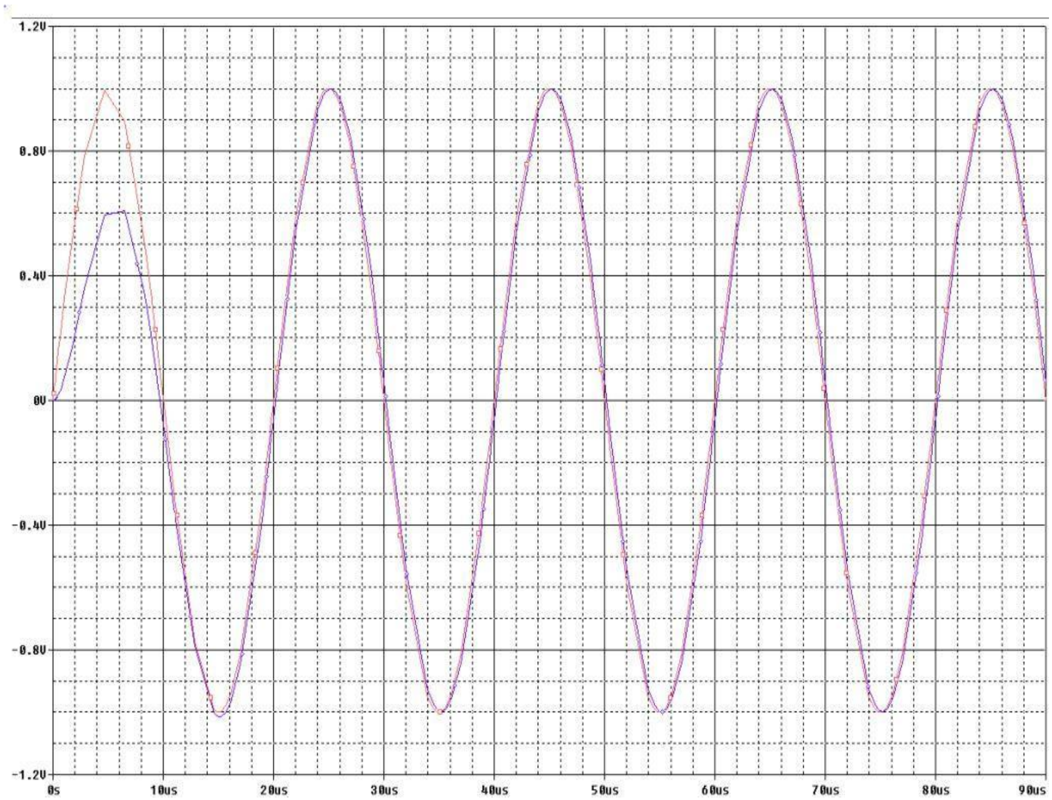
Fig. 4.19 Circuit diagram of high pass filter implemented using GIC.

Fig 4.20-Fig 4.23 show the Frequency Response and Transient response and transient response of these filters for an input amplitude of 100mV pp at a frequency of 1KHz.



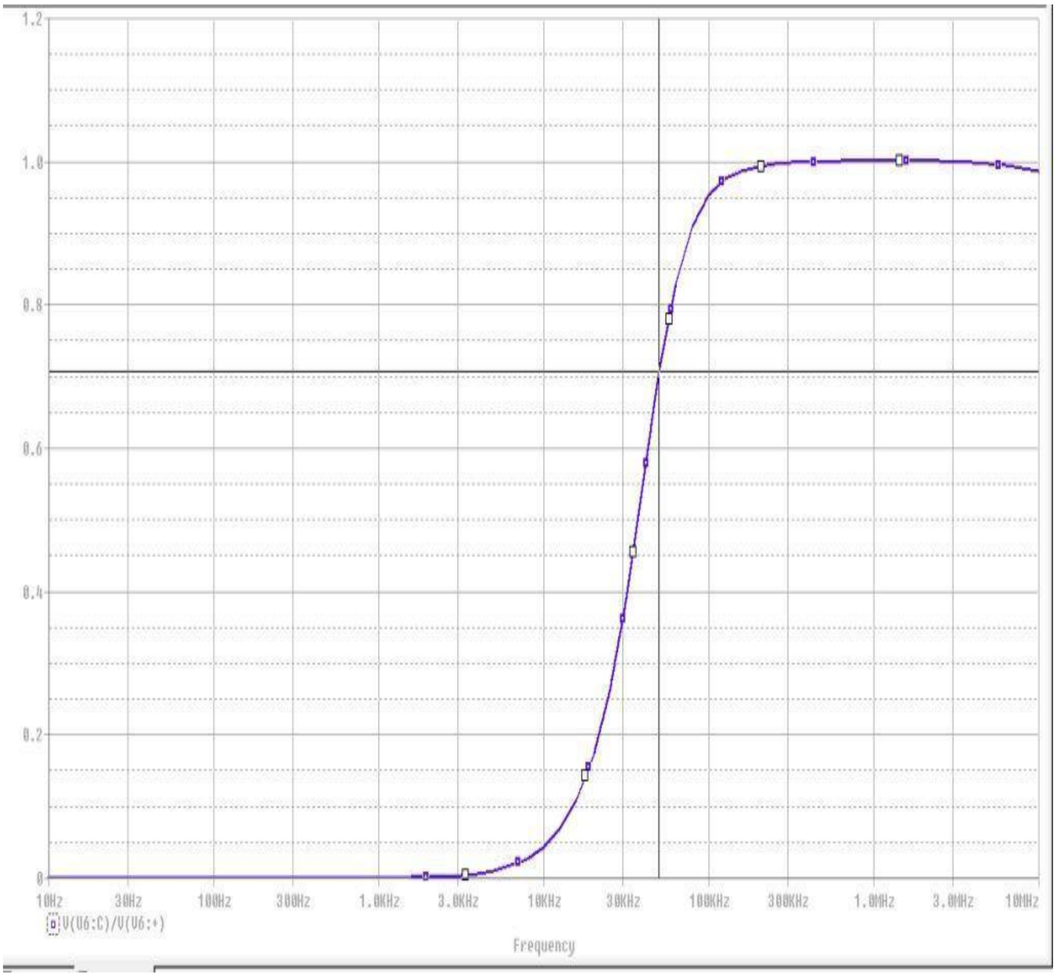
	Trace Color	Trace Name	Y1	
		X Values	50.336K	10
	CURSOR 1,2	V(U6:C)/V(V6:+)	0.9966	1.

Fig 4.20 Frequency response of the GIC derived band pass filter



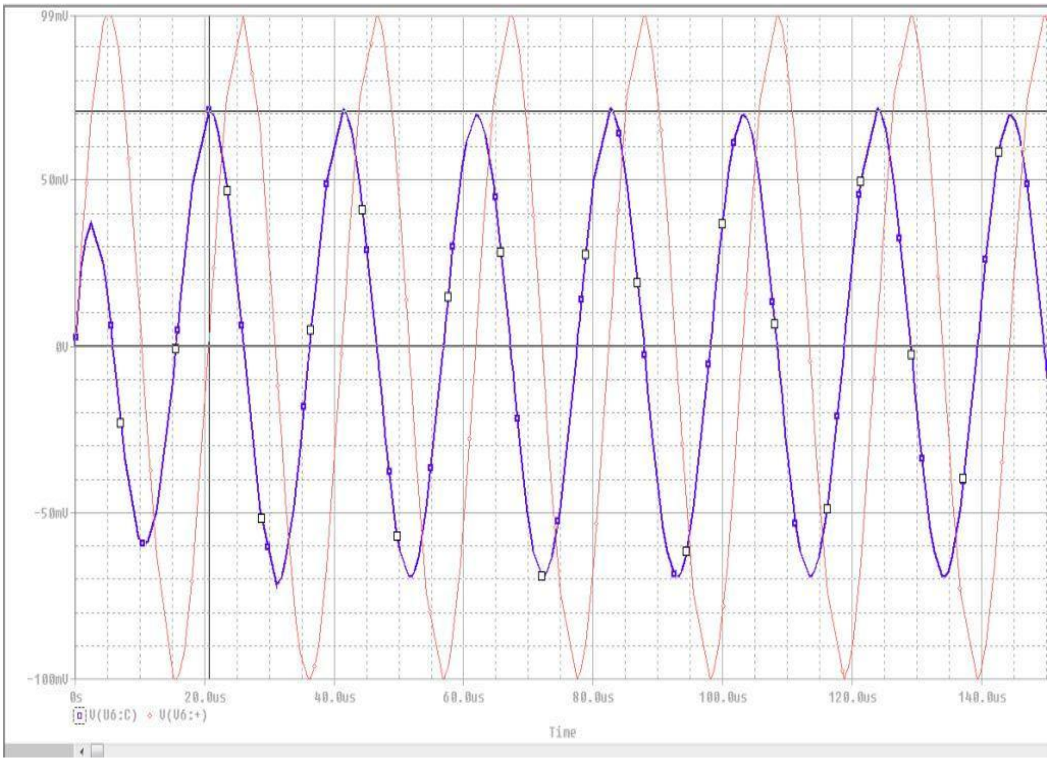
Trace Color	Trace Name	Y1	Y2	Y1 - Y2
	X Values	45.315u	0.000	45.315u
CURSOR 1,2	V(V6:+)	0.9954	0.000	0.9954
	V(U6:C)	994.809m	246.653u	994.562m

Fig 4.21 Transient response of the GIC derived band pass filter at cutoff



Trace Color	Trace Name	Y1	
	X Values	50.185K	1
CURSOR 1,2	V(U6:C)/V(V6:+)	707.586m	2

Fig 4.22 Frequency response of GIC derived High pass filter



	Trace Color	Trace Name	Y1
		X Values	20.699u
	CURSOR 1,2	V(U6:C)	70.635m

Fig 4.23 Transient response of GIC derived High pass filter at cutoff

4.4 CONCLUSION

In this chapter we have presented Single Amplifier based second order filter is presented. The various configurations of second order like Sallen-key, Tow Thomas Biquad and GIC based Biquad has been discussed and are designed using CFOA AD844

CHAPTER 5

HIGHER ORDER FILTER

A higher order filter represents the filter having the order of denominator greater than Sometimes second order filter does not provide sufficient selectivity. So then to meet the requirement of sufficient selectivity higher order filters are designed [11, 12] There are many methods available to design a higher order filter as shown in Fig. 5.1.

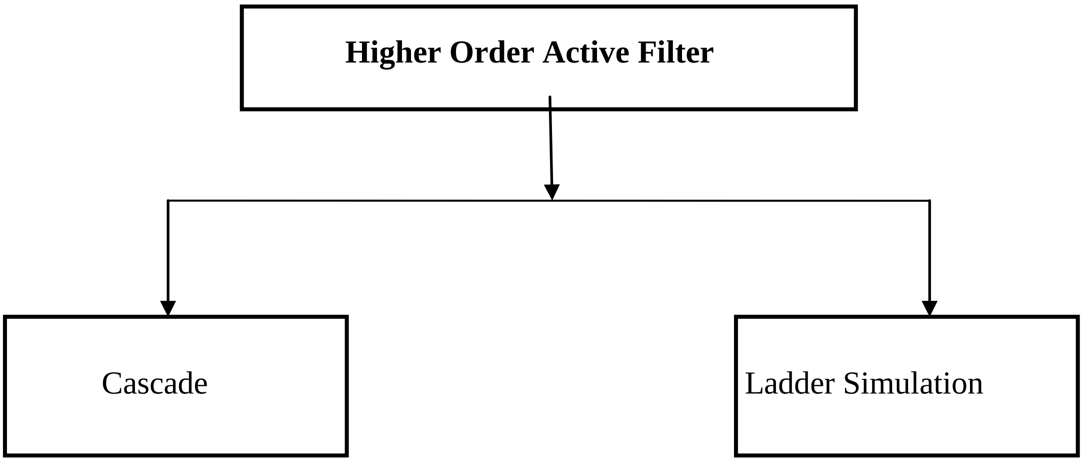


Fig 5.1 Approaches to design higher order active filter

In following we present a brief introduction of both the techniques to design the higher order active filter with one or two filter designed with each technique using CFOA.

5.1 CASCADE DESIGN

In cascade design techniques one can obtain a higher order filter by cascading bilinear (first order) and biquadratic(second order) transfer function. [11]. The transfer function of the higher order filter is factored in terms of first and/or second order transfer function. This is the simplest of all the techniques to realize the higher order filters and this technique is used very frequently in industries and has the following features [6, 11].

a) Ease of implementation.

b) Simple architecture

c) Ease of tuning (usually one active device per pole is needed).

The major disadvantage of the cascaded filter is they are sensitive to parameter variation when we increase the order of filter to eight [12].

Now let us take a higher order transfer function as

$$T(s) = \frac{N(s)}{D(s)}$$

$$= \frac{b_{2m}s^{2m}+b_{2m-1}s^{2m-1}+b_1s+b_0}{s^{2n}+a_{2n-1}s^{2n-1}+\cdots a_1s+a_0} \quad (5.1)$$

Now the transfer function can be factored as

$$T(s) = \frac{V_{out}}{V_{in}} = \frac{V_{01}}{V_{02}} \times \frac{V_{02}}{V_{01}} \times \frac{V_{03}}{V_{02}} \cdots \frac{V_{0(n-1)}}{V_0(n-2)} \times \frac{V_{out}}{V_{0(n-1)}}$$

$$= T_1(s)T_2(s) \ldots . T_{n-1}(s)T_n(s)$$

$$= \prod_{j=1}^{n} T_J(s) \quad (5.2)$$

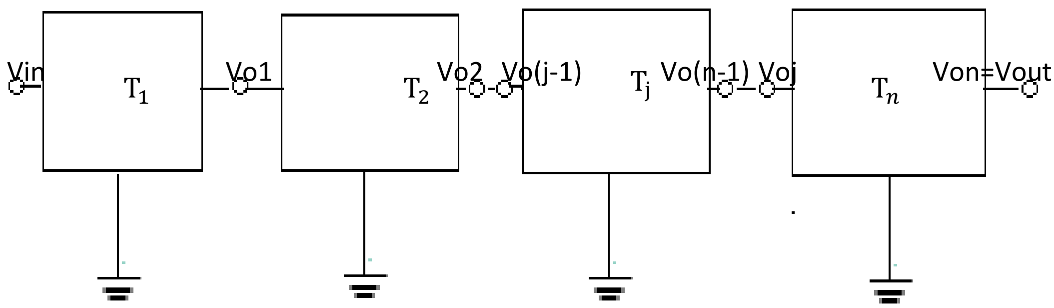


Fig 5.2 Cascade connections of Biquad sections to realize n^{th} order filter [11]

The factored second order terms of the transfer function *T(s)* are all connected in cascade form. Now the designer has to design each Biquad or first order filter section to complete the design of the higher order filter.

All the terms of Eq. 5.2 have even degree of N(s) and D(s) so they can be factored as follows:

$$T(s) = \frac{N(s)}{D(s)} \frac{\prod_{i=1}^{m} k_i(\alpha_{2i}s^2+\alpha_{1i}s + \alpha_{oi})}{\prod_{j=1}^{n}(s^2 + \left(\frac{\omega_{oj}}{Q_j}\right) + \omega_{oj}^2)}$$

$$= \prod_{j=1}^{n} kj \frac{(\alpha_{2j}s^2+\alpha_{1j}s+\alpha_{oj})}{(s^2+\left(\frac{\omega_{oj}}{Q_j}\right)+\omega_{oj}^2)} = \prod_{j=1}^{n} T_j(s) \quad (5.3)$$

The design process of the Eq. 5.3 is very simple and straightforward because the complete transfer function is now divided into standard Biquad sections. The following there are some factors must be considered in cascaded design [6, 12].

i. It should be determined that which zero is assigned to which pole to form $T_j(s)$
ii. The sequencing of the sections i.e. which section will come first and which section will come second and so on should be determined
iii. What will be the gain of each section should be determined."

5.1.1 Butterworth Fifth Order Low Pass Filter

A signal processing filter designed to have as maximally flat response as possible in passband is termed as Butterworth Filter. Butterworth filter is also called as maximally flat magnitude filter. The frequency response of the Butterworth filter rolls off towards zero in stopband. A Butterworth filter monotonically changes function with ω as compared to other filters which have non monotonic ripple in passband and/or stopband. Butterworth filter in comparison to Chebyshev filter have lower roll off so to acquire desired stopband specifications higher order is need to be implemented but these filters have more linear characteristics in passband as compared to Chebyshev filter [29].

Low Pass Filter Specifications

The attenuation of the filter as a function of frequency is defined as follows

$$\alpha(\omega) = -20\log|T_n(\omega)| \tag{5.4}$$

Measured in db, which makes

$$|T_n(\omega)| = 10^{-\alpha(\omega)/20} \tag{5.5}$$

Here $\alpha(\omega)$is a positive no. because $|T_n(\omega)|$ is considered to be less than 1 in passband. Specifications of a low pass filter are given to an engineer in following way which is depicted in figure 5.3 as shown below

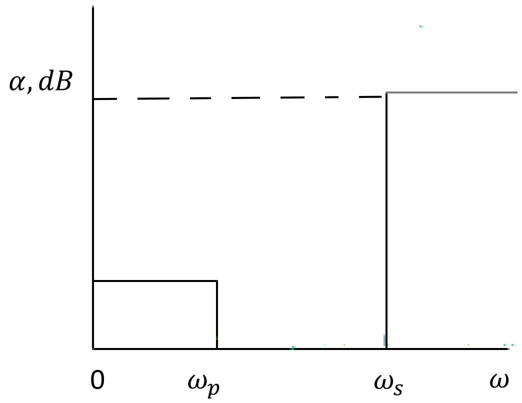


Fig 5.3 Low pass filter specification

For the passband which is extending from $\omega = 0$ to $\omega = \omega_p$ attenuation should not be greater thanα_{max}. From ω_p to ω_s the transition band is there. Also from ω_s to higher frequency the attenuation should not be less than α_{min}. If all the parameters are given the two necessary parameters we need to find are coefficient ϵ^2 and degree n, of the maximally flat transfer function $|T_n(j\omega)|$. So at passband corner we have

$$\alpha_{max} = 10\log(1+\varepsilon^2) \qquad (5.6)$$

Here ε^2 is given by

$$\varepsilon^2 = 10^{0.1\alpha_{max}} - 1 \qquad (5.7)$$

At the stopband corner $\omega = \omega_s$, we have

$$\alpha_{min} = 10\log(1 + (10^{0.1\alpha_{max}} - 1)\omega_s^{2n}) \qquad (5.8)$$

So the degree n can be determined by rearranging Eq. 5.8 for ω_s^{2n} and taking log of the determine equation which yields

$$n = \frac{\log[(10^{0.1\alpha_{min}} - 1)/10^{0.1\alpha_{max}} - 1]}{2\log\omega_s} \qquad (5.9)$$

The formula for finding the denormalized -3dB down frequency is given by

$$\omega_B = \epsilon^{-1/n}\omega_p \qquad (5.10)$$

5.1.2 Design of Fifth Order Butterworth Filter

A fifth order Butterworth filter with the following specifications was designed:

$$\alpha_{max} = 0.5dB \quad \alpha_{min} = 20dB \quad \omega_p = 1000rad/s \quad \omega_s = 2000rad/s$$

So according to the specification and using Eq. 5.9 the degree n of the filter is found to be 4.83 which is round off to 5. So the filter designed by these specifications is a fifth order filter. In order to use the Butterworth table for pole locations we need to find the denormalized frequency by using Eq. 5.10

$$\omega_B = 6171\, rad/s \qquad (5.11)$$

The Pole locations of fifth order Butterworth filter is selected from Table 1 of appendix . The poles selected are as follows

$s = -1 \quad s = -0.8090170 \pm j0.5877852 \quad s = -0.3090170 \pm j0.951056$

So according to above pole locations the Transfer function of the Fifth order Butterworth low pass filter is given by

$$T(s) = \frac{N(s)}{D(s)} = \frac{1}{(s+1)(s^2+1.6180s+1)(s^2+0.6180s+1)} \qquad (5.12)$$

Where$s = s/\omega_n$,

The fifth order filter is designed by cascading a First order filter and two Second order filter. Second order filter used here is of Sallen-Key configuration.

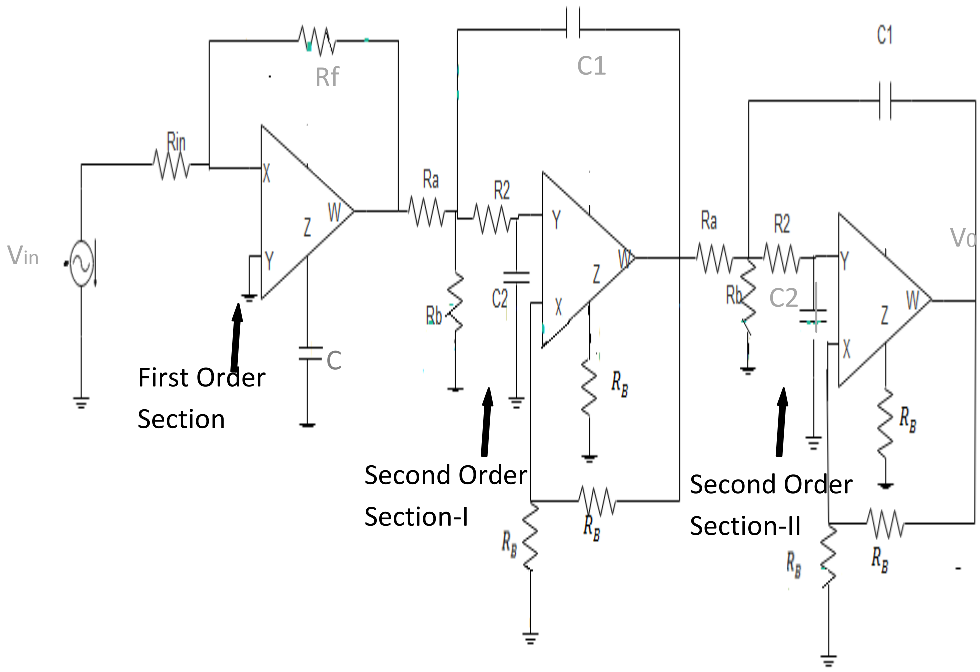


Fig 5.4 Fifth order Butterworth low pass filter circuit diagram

Now we break the transfer function into three sections

$$T(s) = T_1T_2T_3 = \frac{k_1}{s+1}\,\frac{k_2}{s^2+1.6180s+1}\,\frac{k_3}{s^2+0.6180s+1} \qquad (6.13)$$

Where we have assigned three gain constantsk_1, k_2 and k_3 whose product must equal 1.The sections are arranged in the order of increasing values of Q.($Q_1 = 0.5 < Q_2 = 0.618 < Q_3 = 1.618$).

First Order Section

So for the first order module we have $C = 0.1uF, R_{in} = 1.62K\Omega\ and\ R_f = 1.62K\Omega$. The value of the Resistor used here is derived according to the following criteria

$$T(s) = \frac{G_1/C}{s + G_2/C} = \frac{1}{s+1} \tag{5.14}$$

Here we have taken C=0.1uF and $\omega_B = 6171\ rad/s$ so value of resistors used in first order can be obtained as

$$R_1 = R_2 = \frac{1}{\omega_B C} = 1.62K\Omega$$

Second Order Section-I

So for the second order module-I we have $R_a = 2.23K\Omega$, $R_b = 5.86K\Omega$ $R_2 = 1.62K\Omega$,$R_A = 10K\Omega$ and $R_B = 17.6K\Omega$ and $C_1 = 0.1uF$ and $C_2 = 0.1uF$. The value of R_a, R_b and R_2 is derived according to following criteria.

$$T(s) = \frac{aK\omega_0^2}{s^2 + \frac{s\omega_0}{Q} + \omega_0^2} \tag{5.16}$$

Since the filter is of Sallen-key configuration we have $\omega_0 = 1/(RC)$ and $Q = 1/(3 - K)$. Then we get

$$T_2(s) = \frac{aK\omega_0^2}{s^2 + \frac{s\omega_0}{Q} + \omega_0^2} = \frac{1}{s^2 + 1.6180s + 1} \tag{5.17}$$

The value of R obtained with value of C=0.1uF and $\omega_B = 6171\ rad/s$ is given as follows

$$R = \frac{1}{\omega_B C}, \qquad K = 3 - Q^{-1} = 1.382, \qquad a = 1/K = 0.724$$

Second Order Section-II

So for the second order module-I we have $R_a = 3.89K\Omega$, $R_b = 2.75K\Omega$ $R_2 = 1.62K\Omega$,$R_A = 10K\Omega$ and $R_B = 37.6K\Omega$ and $C_1 = 0.1uF$ and $C_2 = 0.1uF$. The value ofR_a, R_b and R_2 is derived according to following criteria.

$$T_3(s) = \frac{aK\omega_0^2}{s^2 + \frac{s\omega_0}{Q} + \omega_0^2} = \frac{1}{s^2 + 0.6180s + 1} \qquad (5.18)$$

We find

$$R = \frac{1}{\omega_B C}, \qquad K = 3 - Q^{-1} = 2.382, \qquad a = \frac{1}{K} = 0.420 \qquad (5.19)$$

A fifth order Butterworth low pass filter was designed to give a DC gain of 1 and Cut-off frequency of 981Hz. The transient response of circuit filters for input amplitude of 100mV pp at a frequency of 100Hz is shown in Fig. 5.5. The Frequency Response of the circuit is shown in Fig. 5.6

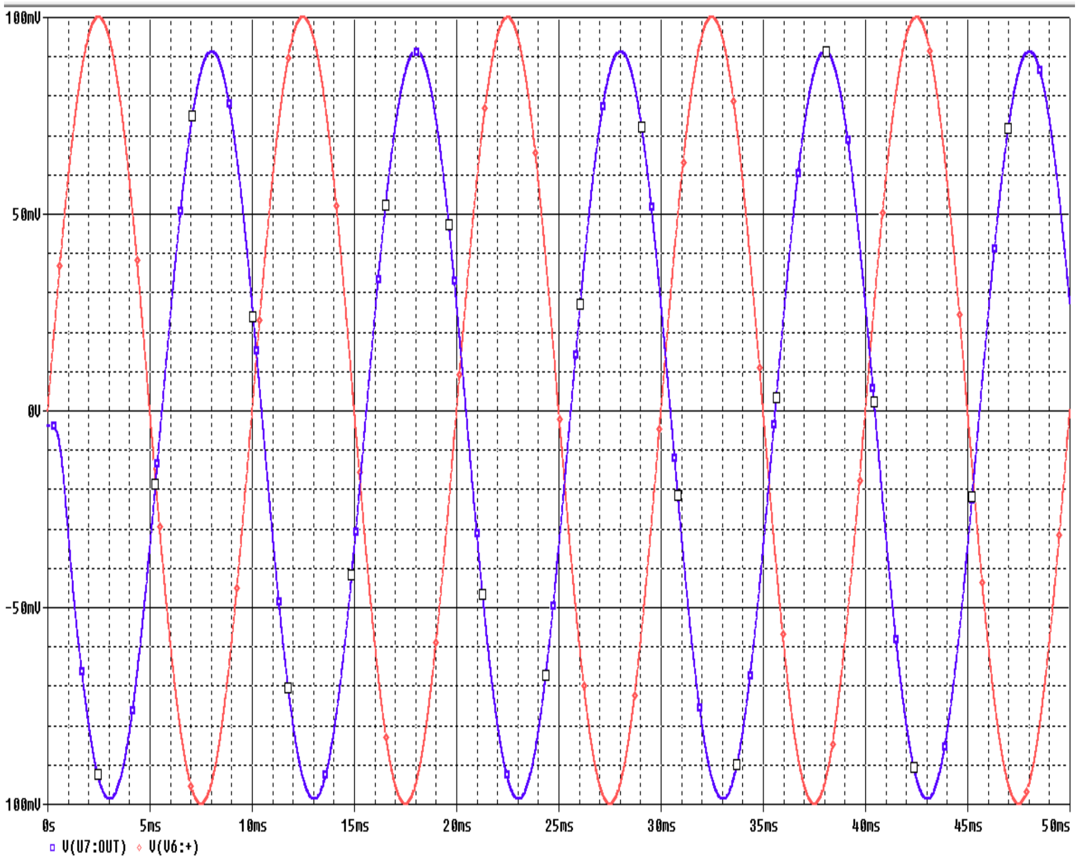
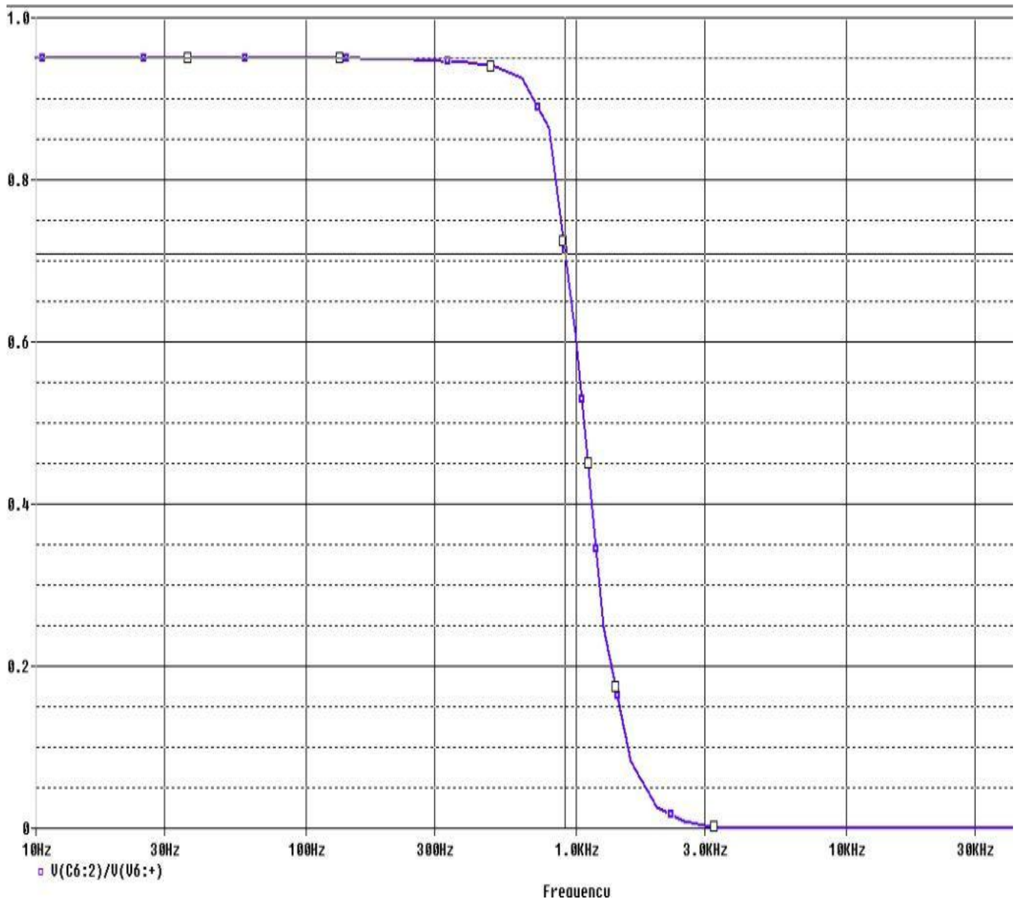


Fig. 5.5 Simulated Transient response of Butterworth fifth order low pass filter



Trace Name	Y1
X Values	910.250
V(C6:2)/V(V6:+)	708.621m

Fig 5.6 Simulated Frequency response of Butterworth fifth order low pass filter

5.1.3 Chebyshev third order low pass filter

The analog or digital filter having steeper Roll-off is termed as Chebyshev Filters. There are two types of Chebyshev filter: Type I in which there are ripples in passband and Type II in which ripples are present in stopband. The type I filters are usually called as Chebyshev filters while the type II are called as Inverse Chebyshev filters The roll-off of the Chebyshev filter is steeper than the Butterworth filter. The Chebyshev filters have a advantage that they minimized the error which is present between the ideal and actual filter characteristics over the entire filter range with the drawback of having ripples in passband. The type I filters are usually called as Chebyshev filters while the type II are called as Inverse Chebyshev filters.

The Chebyshev magnitude response is given by Eq. 5.20.

$$|T(j\omega)|^2 = \frac{1}{1+\varepsilon^2 C_n^2(\omega)} \tag{5.20}$$

The attenuation of the Chebyshev filters are our case id given by Eq. 5.21

$$\alpha_n = -10\log|T(j\omega)|^2 = 10\log|1+\varepsilon^2 C_n^2(\omega)|\ dB \tag{5.21}$$

A figure depicting the above magnitude response showing the rippling nature of the Chebyshev filters in the passband$\omega \le 1$ and rapid rise to large values of attenuation when $\omega > 1$. The minimum attenuation of the filter is given by Eq. 5.22

$$\alpha_{min} = 10\log[1+\varepsilon^2 cosh^2(n\ cosh^{-`1}\omega_s)]\ dB \tag{5.22}$$

We always specify the maximum passband attenuation α_{max} and then determine the minimum stopband attenuation α_{min} and the transition bandwidth between passband and stopband ϵ and the degree n of the filter that realizes these specifications by following given equations.

$$\varepsilon = \sqrt{10^{\frac{\alpha_{max}}{10}} - 1}$$

$$n \approx \frac{\ln\sqrt{4(`10^{0.1\alpha_{min}} - 1)/(10^{0.1\alpha_{max}} - 1)}}{\ln\left(\omega_s + \sqrt{\omega_s^2 - 1}\right)} \tag{5.23}$$

5.1.4 Design of Third Order Chebyshev Filter

A Third order Chebyshev filter with the following specifications was designed:

$$\alpha_{max} = 1dB \quad \alpha_{min} = 22dB \quad \omega_p = 1 \quad \omega_s = 2.33$$

By using Eq. 5.23 we can compute the degree of function which is equal to approximately equal to 3 after rounding off. Now to determine the poles location we will use the Table 2 of the Appendix showing the Chebyshev pole locations.

$$s_1 = -0.494, \quad s_2, s_3 = -0.247 \pm j0.966$$

The transfer function of third order Chebyshev filter is given as

$$T(s) = \frac{0.5}{(s+0.494)(s^2+0.494s+0.994)} \tag{5.24}$$

The third order Chebyshev low pass filter is designed by cascading a first order low pass filter with a second low pass filter of the Sallen-key configuration. Now we will factor this transfer function into two section to implement a first order and second order transfer function.

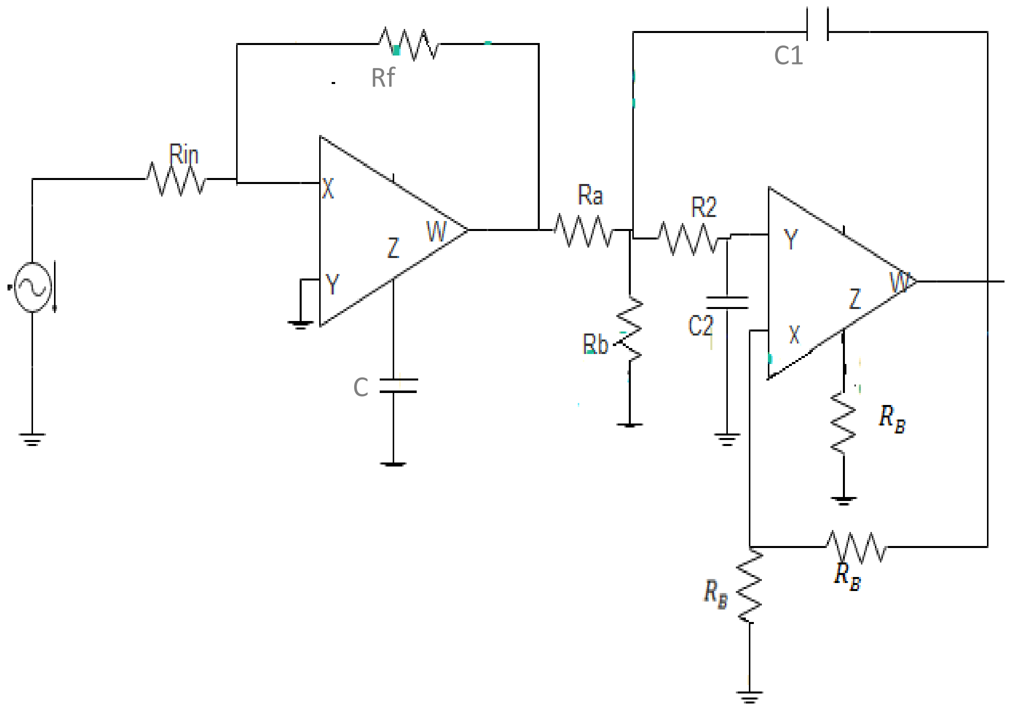


Fig 5.7 Circuit diagram of Chebyshev Third order low pass filter

$$T(s) = T_1T_2 = \frac{k_1}{s+0.494}\,\frac{k_2}{s^2+0.494s+0.994} \qquad (5.25)$$

Here the product of k_1 and k_2 should be equal to 0.5 and the Q factor of the first order filter and second order filter is $Q = 0.5$ and $Q = 2.018$ respectively

$$T(s) = T_1T_2 = \frac{0.49}{s+0.494}\,\frac{0.99}{s^2+0.494s+0.994} \qquad (5.26)$$

First Order Section

So for the first order module we have $C = 0.1uF, R_{in} = 20K\Omega\ and\ R_f = 20K\Omega$. The value of the Resistor used here is derived according to the following criteria

$$T(s) = \frac{G_1/C}{s+G_2/C} = \frac{0.49}{s+0.494} \qquad (5.27)$$

Here we have taken C=0.1uF and $\omega_{01} = 494\,rad/s$ so value of resistors used in first order can be obtained as

$$R_1 = R_2 = \frac{1}{\omega_{01}C} = 20K\Omega \qquad (5.28)$$

Second Order Section

So for the second order module we have $R_a = 25K\Omega$, $R_b = 17K\Omega$ $R_2 = 10K\Omega$,$R_A = 10K\Omega$ and $R_B = 40K\Omega$ and $C_1 = 0.1uF$ and $C_2 = 0.1uF$. The value of R_a, R_b and R_2 is derived according to following criteria

For the second order section we will choose $C_1 = C_2 = C\ and G_1 = G_2 = G = 1/R$

$$T(s) = \frac{aK\omega_0^2}{s^2 + \frac{s\omega_0}{Q} + \omega_0^2} \tag{5.29}$$

Since the filter is of Sallen-key configuration we have $\omega_0 = 1/(RC)$ and $Q = 1/(3 - K)$. Then we get

$$T_2(s) = \frac{aK\omega_0^2}{s^2 + \frac{s\omega_0}{Q} + \omega_0^2} = \frac{1}{s^2 + 0.494s + 0.994} \tag{5.30}$$

The value of R obtained with value of $C = 0.1uf$ and $\omega_{02} = 994\ rad/s$ is given as follows

$$R = \frac{1}{\omega_B C}, \qquad K = 3 - Q^{-1} =, \qquad a = 1/K = 0.724$$

$$T_3(s) = \frac{aK\omega_0^2}{s^2 + \frac{s\omega_0}{Q} + \omega_0^2} = \frac{1}{s^2 + 0.6180s + 1} \tag{5.31}$$

We find

$$R = \frac{1}{\omega_B C}, \qquad K = 3 - Q^{-1} = 2.504, \qquad a = \frac{1}{K} = 0.396 \tag{5.32}$$

A third order Chebyshev low pass filter was designed to give a DC gain of 1 and Cut-off frequency of 160Hz. The transient response of circuit filters for an input amplitude of 100mV pp at a frequency of 100Hz is shown in Fig. 5.8. The Frequency Response of the circuit is shown in Fig. 5.9

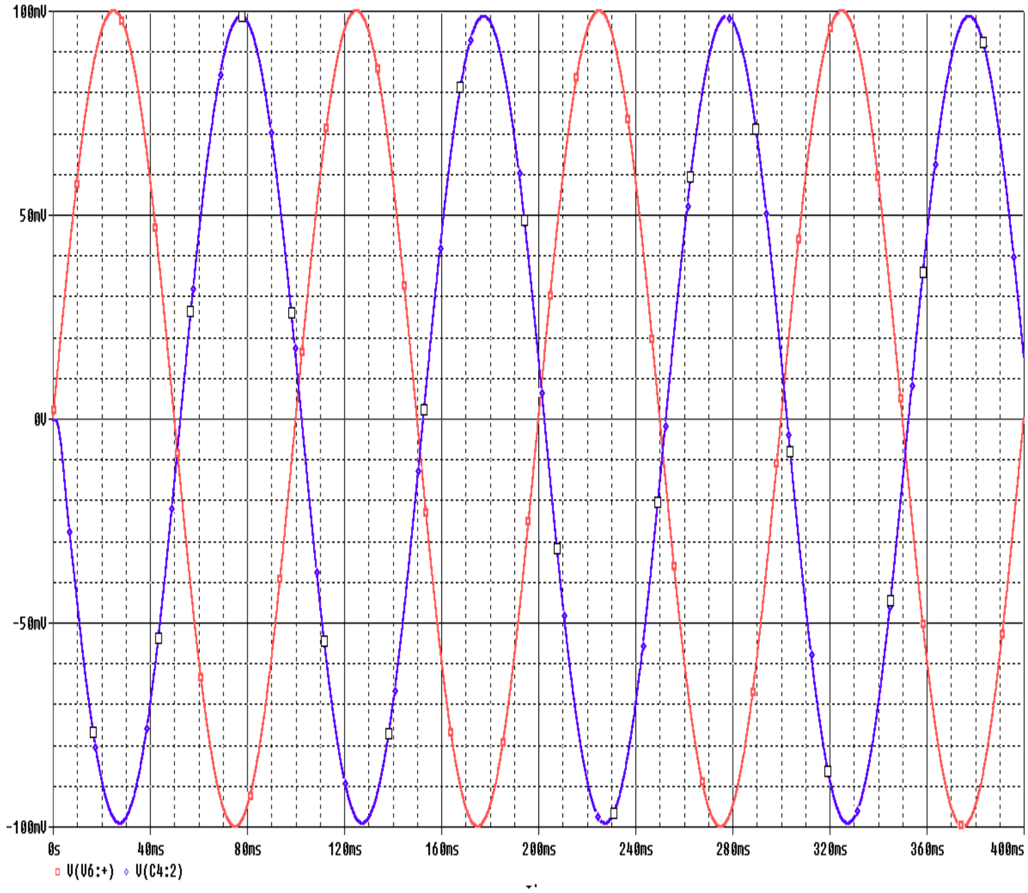
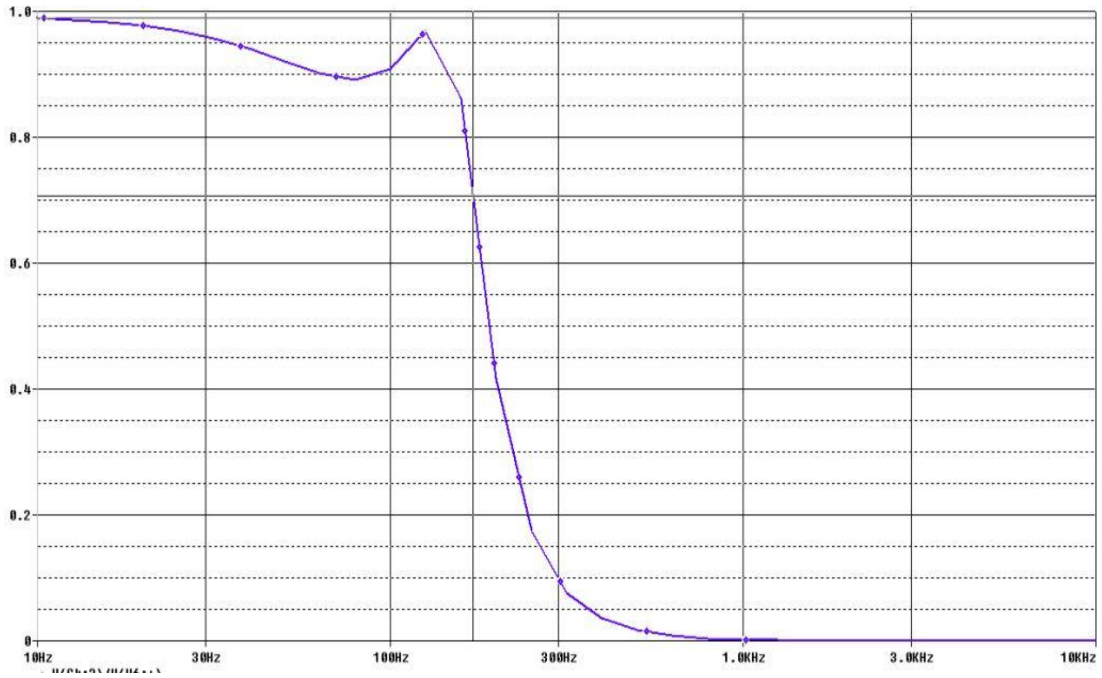


Fig 5.8 Simulated transient response of Chebyshev third order low pass filter



	Trace Color	Trace Name	Y1	Y2	Y1 - Y2
		X Values	171.784	10.000	161.784
	CURSOR 1,2	V(C4:2)/V(V6:+)	706.897m	989.165m	-282.268r

Fig 5.9 Simulated frequency response of Chebyshev third order low pass filter

5.2 LADDER SIMULATION

It is known that resistively terminated passive LC ladders offer very low sensitivity to parameter variations. Also we have a large amount of information in form of tables to design LC ladder filters. Major drawback of designing the LC ladder is we have to realize the inductor which is a very heavy and bulky process especially for low frequency operations. Also it is very difficult to construct the inductors for the use of microelectronics circuits because they are used in monolithic form there.

The LC ladder simulation is broadly subdivided into three parts: Elements Replacement, Operational Simulation and Wave active filter approach. Since the designing method chosen in this dissertation is Operational simulation so it is only described in detail in further paragraphs. A LC prototype exists before the active simulation.

5.2.1 Operational Simulation

In this technique operation of ladder is simulated. So to describe this approach we will design a Fourth order low pass LC ladder filter. A ladder circuit is shown in figure below in which current through the series branch and voltage across the shunt branch are taken as state variables [6].

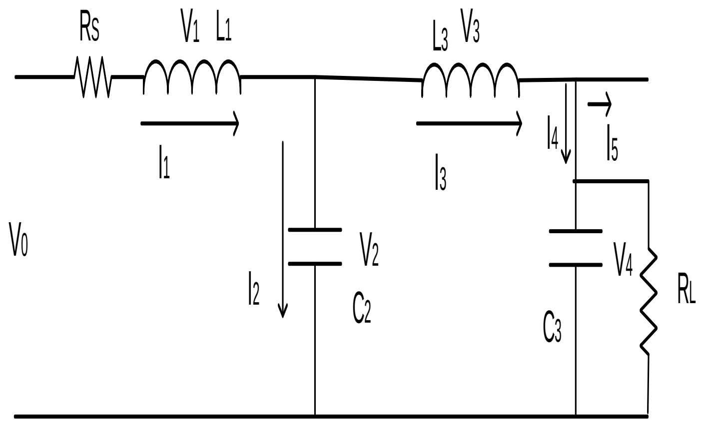


Fig. 5.10 Fourth order LC low pass ladder

$$V_1 = V_0 - V_{2,}\ V_3 = V_2 - V_4 \quad (5.33)$$

$$I_2 = I_1 - I_3, I_3 = I_4 \quad (5.34)$$

Here it has been assumed that the current I_5 is equal to zero. Further we will describe the V-I relationships for the series and the shunt branches of the ladder.

$$I_1 = \frac{V_1}{sL_1+R_S}\ , I_3 = \frac{V_3}{sL_3} \quad (5.35)$$

$$V_2 = \frac{I_2}{sC_2}, V_4 = \frac{I_4}{sC_4} \quad (5.36)$$

From above equations we can conclude that we need circuit which together can perform the difference of two voltages or current and also perform lossless or lossy integration. So here first we will describe about the lossy and lossless integrator circuit designed using CFOA. Consider the ladder circuit shown above we have describe the components connected in series as Y_i and those in shunt branches as Z_i.So we can describe the ladders by following equations.

$$I_1 = Y_1(V_0 - V_2) \tag{5.37}$$

$$V_2 = Z_2(I_1 - I_3) \tag{5.38}$$

$$I_3 = Y_3(V_2 - V_4) \tag{5.39}$$

$$V_4 = Z_4(I_3 - I_5) = Z_4 I_3 \tag{5.40}$$

Where $Y_1 = \frac{1}{sL_1+R_S}$ $\quad Z_2 = \frac{1}{sC_2}$ $\quad Y_3 = \frac{1}{sL_3}$ $\quad Z_4 = \frac{1}{sC_4+G_L}$

To design this circuit we will scale the above equations by a scaling resistor R_P. From equation 5.5 we obtain

$$R_P I_1 = R_P Y_1(V_0 - V_2) \longrightarrow v_{I1} = t_{Y1}(v_0 - v_2) \tag{5.41}$$

Here we have replaced the $R_P I_1$ with lower case symbol v_{I1} and the subscript I is retained so that we know that this voltage was derived from a current in the circuit. The dimensionless quantity $R_P Y_1$ is labeled as t_{Y1} because it is a transfer function. Similarly we obtain from other equations 5.37 to 5.40

$$V_2 = \frac{Z_2}{R_P}(R_P I_1 - R_P I_3) \longrightarrow v_2 = t_{Z2}(v_{I1} - v_{I3}) \tag{5.42}$$

$$R_P I_1 = R_P Y_1(V_0 - V_2) \longrightarrow v_{I3} = t_{Y3}(v_2 - v_4) \tag{5.43}$$

$$V_4 = \frac{Z_4}{R_P}(R_P I_3 - R_P I_5) \longrightarrow v_2 = t_{Z4} v_{I3} \tag{5.44}$$

Where t_{Yi} and t_{Zi} are the transfer functions that represents the ratio of two voltages. Here $RI_i$are represented as voltages of the form of v_{Ii} where subscript ‘I’ is retained to remind that these quantities are transformed from currents in the circuits. To maintain the notation all other voltages are also represented in lower cases. In Op-amps the addition of two voltages is quite easier than subtraction. So the transfer functions of impedances t_{Zi} are replaced by $-t_{Zi}$. The same replacement can be done witht_{Yi}. Now replacing t_{Zi} by $-t_{Zi}$ and keeping the track of the minus signs, the Eqs.5.42-5.44 can be modified as

$$v_{I1} = t_{Y1}[v_0 + (-v_2)] \tag{5.45}$$

$$-v_2 = -t_{Z2}[v_{I1} + (-v_{I3})] \tag{5.46}$$

$$-v_{I3} = t_{Y3}\left[(-v_{2)} + v_4\right] \tag{5.47}$$

$$v_4 = -t_{Z4}(-v_{I3}) \tag{5.48}$$

All the equation from 5.45 to 5.48 depicts the functional behavior of ladder circuit. So to simulate these equations we require lossy and lossless integrators as t_{Y1} and t_{Z4} are lossy and rest of the two are lossless integrators. Thus to perform the operational simulation of ladder circuit we need inverting and non inverting lossy/lossless integrators which integrates the sum of two voltages.

Fourth order LC ladder low pass filter specifications

Since the ladder circuit designed here is fourth order Chebyshev low pass with ripple bandwidth 0.1db so normalized values used for inductor and capacitor are given as follows which are selected from the Table III given in Appendix

$$L_1 = 1.10879 \;\; C_2 = 1.30618 \;\; L_3 = 1.77035 \;\; C_4 = 0.81807$$

$$R_2 = 0.7378 = 1/1.3554$$

$$t_{Y1} = \frac{1}{sL_1/R_P + R_S/R_P} = \frac{1}{s1.10879/\, R_P + 1/R_P}$$

$$t_{Z2} = \frac{1}{sC_2R_P} = \frac{1}{s1.30618R_P}$$

$$t_{Y3} = \frac{1}{sL_3/R_P} = \frac{1}{s1.77035/R_P}$$

$$t_{Z4} = \frac{1}{sC_4R_P + G_2R_P} = -\frac{1}{s0.81807R_P + 1.3554R_P}$$

For the first active integrator circuit we have

$$v_{I1} = \frac{1}{s1.10879/R_P + 1/R_P}[v_0 + (-v_2)]$$

$$= \frac{1}{sCR_a + G_LR_a}\left[\frac{R_a}{R_1}v_0 + \frac{R_a}{R_2}(-v_2)\right]$$

$$\frac{1}{sCR_a + G_L R_a} = \frac{1}{s/1.10879\ R_P + 1/R_P}$$

After de normalizing the passive ladder elements we obtain

$$CR_a = \frac{1.1087 \times \left(\frac{R_S}{\omega_C}\right)}{R_P} \quad and\ \frac{R_a}{R_F} = \frac{R_S}{R_P}$$

Let us choose $C = 0.5nF$ and $R_S = 1.2K\Omega$

$$R_P R_a = \frac{1.1087 \times (R_S/\omega_C)}{C} = 7.82K\Omega$$

Let us take $R_a = R_1 = R_2 = 2K\Omega$ thus will give $R_P = 3.91K\Omega$

$$R_F = \frac{R_s R_P}{R_S} = 6.6K\Omega$$

Now for second active integrator circuit we have

$$-v_2 = \frac{1}{s1.30618R_P}[v_{I1} + (-v_{I3})]$$

$$= \frac{1}{sCR_a}\left[\frac{R_a}{R_1}v_{I1} + \frac{R_a}{R_2}(-v_{I3})\right]$$

$$CR_a = \frac{1.30618 \times R_P}{R_S\omega_C}$$

With $C = 0.5nF$ and $R_S = 1.2K\Omega$

$$\frac{R_a}{R_P} = \frac{1.30618}{R_S\omega_C C} = \frac{1.30618}{1.2k \times 0.5nF \times 340k} = 6.4$$

Since $R_P = 3.91K\Omega$ $R_a = R_1 = R_2 = 25K\Omega$

Proceeding with the third integration circuit we have

$$-v_{I3} = \frac{1}{s1.77035/R_P}[(-v_2) + v_4]$$

$$= \frac{1}{sCR_a}\left[\frac{R_a}{R_1}(-v_2) + \frac{R_a}{R_2}v_4\right]$$

$$CR_a = \frac{1.77035 \times \left(\frac{R_S}{\omega_C}\right)}{R_P}$$

With $C = 0.5nF$ and $R_S = 1.2K\Omega$

$$R_a = \frac{1.77035 \times (R_S/\omega_C)}{R_P C} = 3.19K\Omega = R_1 = R_2$$

Finally for the last integrator circuit we have

$$v_4 = -\frac{1}{s0.81807R_P + 1.3554R_P}(-v_{I3})$$

$$= \frac{1}{sCR_a + G_L R_a}\left[\frac{R_a}{R_1}(-v_{I3})\right]$$

$$CR_a = \frac{0.81807 \times R_P}{R_S \omega_C} \quad and \; G_F R_a R_S = 1.3554R_P$$

$$R_a = \frac{0.81807 \times R_P}{R_S C \omega_C} = R_1 = 15.8k \text{ and } \frac{R_a R_S}{1.3554R_P} = 3.6K\Omega$$

So the values of the passive ladder components calculated according to the Equations given above are

$$L_1 = 3.91mH \quad \text{And} \quad L_3 = 6.23mH$$

$$C_2 = 3.19nF \text{ And } C_4 = 1.91nF$$

$$R_1 = 1.2K\Omega \text{ And } R_2 = 880\Omega$$

A fourth order LC ladder low pass filter was designed with the following components value$R_1 = 2K\Omega = R_2$, $R_3 = 6.6K\Omega$, $R_4 = R_5 = 1K\Omega$ $R_6 = 25K\Omega$, $R_7 = R_8 = 3.19K\Omega$, $R_9 = R_{10} = 1K\Omega$, $R_{11} = 25K\Omega$, $R_{12} = 15.8K\Omega$ and $R_{13} = 3.6K\Omega$ and $C = 0.5nF$ to give a DC gain of 0.423 and the cut-off frequency of 57K. The transient response of circuit filters for input amplitude of 100mV pp at a frequency of 1KHz is shown in Fig. 5.12. The Frequency Response of the circuit is shown in Fig. 5.13

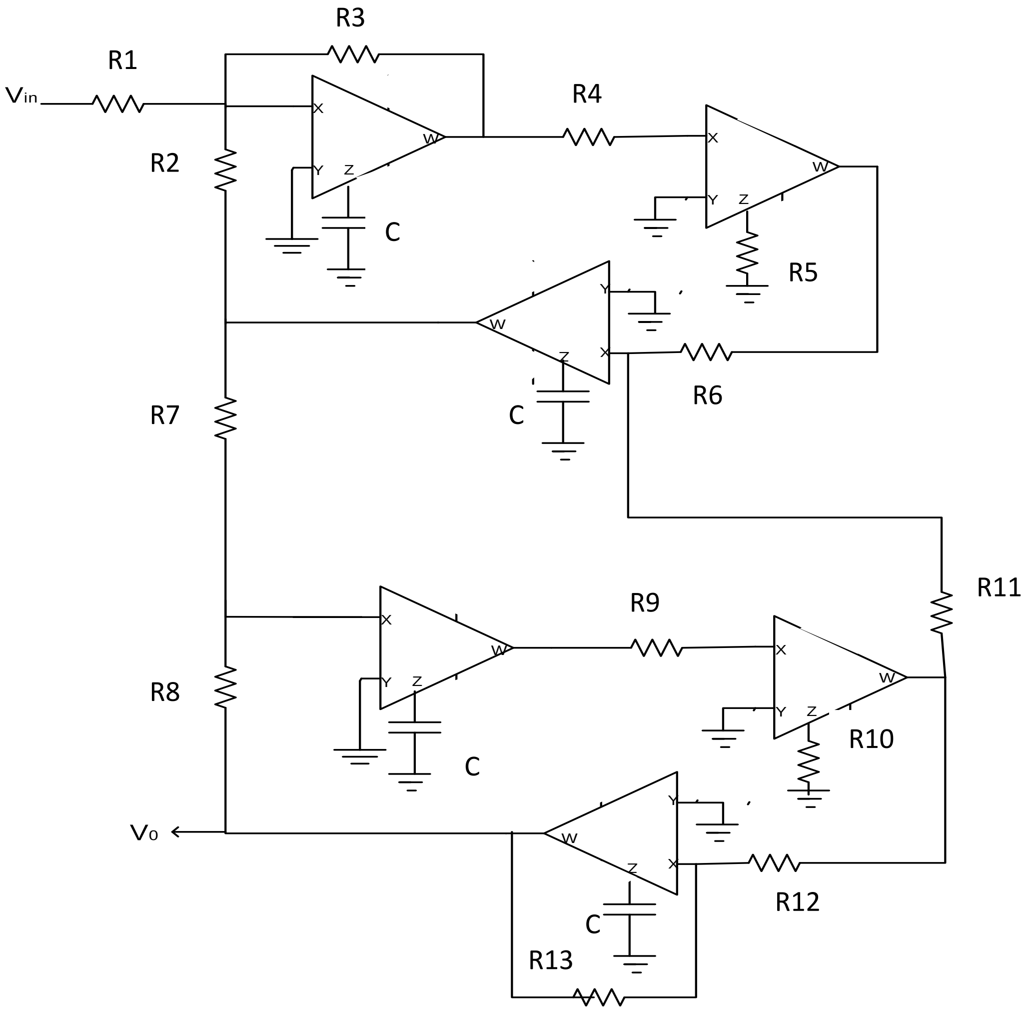


Fig 5.11 Active realizations of Low pass Ladder of Fig 5.8

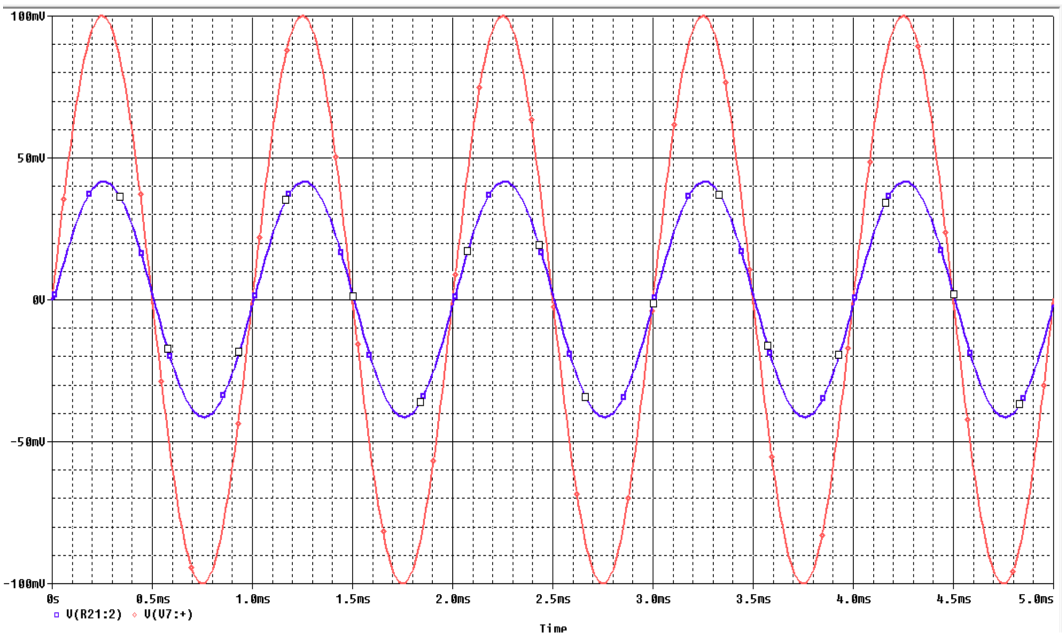
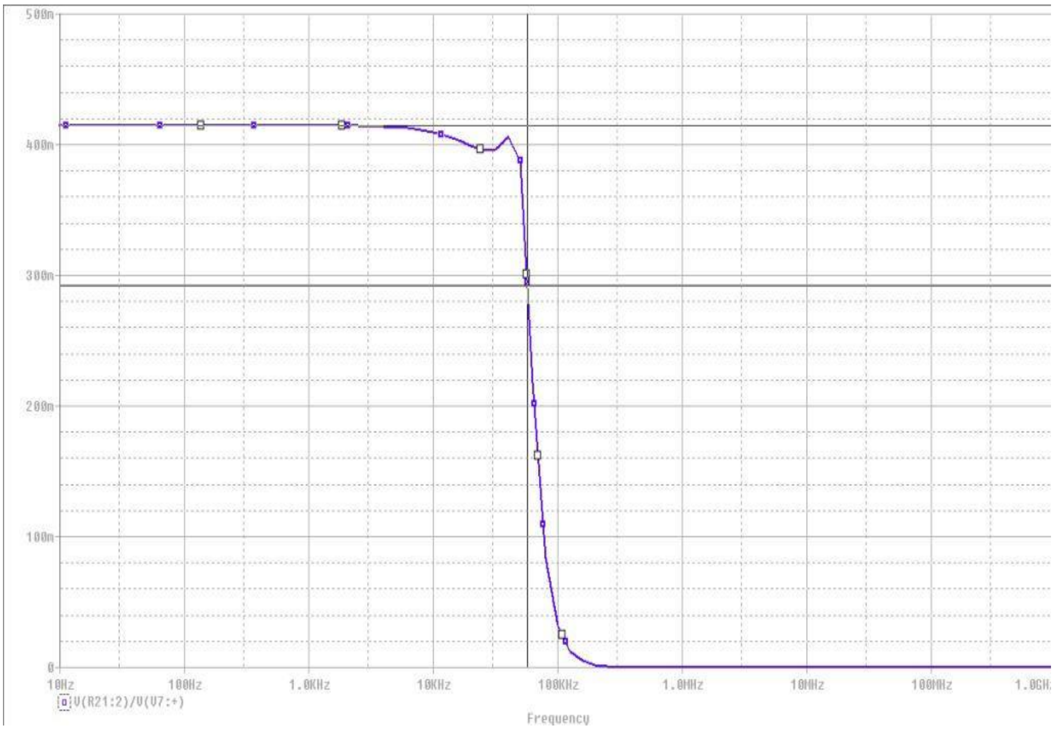


Fig 5.12 Simulating transient response of Fourth order LC low pass filter



Trace Color	Trace Name	Y1	Y2
	X Values	57.049K	10.000
CURSOR 1,2	V(R21:2)/V(V7:+)	292.241m	414.77

Fig 5.13 Simulating Frequency response of Fourth order LC low pass filter.

5.3 CONCLUSION

In this chapter two methods of designing higher order filters such as cascade design and ladder simulation are discussed in brief. A Butterworth and a Chebyshev low pass filter are designed using cascading technique. Fourth order ladder is realized by Operational simulation method . LC ladder simulation techniques is used because it has better sensitivity results as compared to cascading technique.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

In the present work, various filters like Sallen-key, Tow Thomas, Butterworth have been designed by using Current feedback operational amplifier AD844.

In chapter 1 an introduction of filters is presented. Several classification based on different attributes are discussed. Different characteristics according to the degree of the filters have been presented.

In chapter 2 details about CFOA AD844, its functional and internal architecture are discussed in brief. To derive the characteristics equations internal diagram is explain further. An inverting amplifier is designed by using CFOA. Three different gain values are taken and bandwidth is calculated accordingly and simulation results are checked for the bandwidth to prove the gain bandwidth independence of CFOA.

In chapter 3 several first order filter are realized using CFOA AD844. First order low pass, high pass and all pass filters are designed using their standard transfer function and characteristics of CFOA. Also a Bilinear function is implemented by using the characteristics of CFOA and standard notation for bilinear transfer function.

Chapter 4 is dedicated to detailed discussion on second order filter. The various configurations of second order like Sallen-key, Tow Thomas Biquad and GIC based biquad have been discussed and are designed using CFOA-AD844. Sallen-key configuration based low pass and high pass filters are designed and simulated.GIC derived Biquad was designed by replacing the inductor in the standard circuit of band pass and high pass filter with the simulated grounded inductor by using CFOA.

In chapter 5 two methods of designing higher order filters are discussed. These methods can be classified broadly in three categories cascade design and LC ladder simulation techniques. The operational simulation method of LC ladder simulation is discussed in brief. A Butterworth and a Chebyshev low pass filter are designed using cascading technique. Fourth order ladder is realized by Operational simulation method.

Scope for future work:

In this dissertation our focus was on realization of filters using AD844 type CFOAs. But over the years many CMOS realizations have appeared in literature. These CMOS CFOAs in conjunction with voltage buffers, current buffers and Transconductance amplifiers may lead to realization of RC- active filters in fully integrated form resulting into reduction of the size of the filters. Thus the work presented in this dissertation may be extended in this direction.

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APPENDIX

$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$
-0.7071068 $\pm j0.7071068$	-0.5 $\pm j0.8660254$ -1	-0.9238795 $\pm j0.3826834$ -0.3826834 $\pm j0.9238795$	-0.8090170 $\pm j0.5877853$ -0.3090170 $\pm j0.9510565$ -1	-0.2588190 $\pm j0.9659258$ -0.7071068 $\pm j0.7071068$ -0.9659258 $\pm j0.2588190$

Table 1: Pole locations for Butterworth Response

	α_{max}(0.5dB)		α_{max}(0.5dB)		α_{max}(0.5dB)	
n	α	β	α	β	α	β
1	2.8628	0	1.9652	0	1.3076	0
2	0.7128	1.0040	0.5489	0.8951	0.4019	0.8133
3	0.3132	1.0219	0.2471	0.9660	0.1845	0.9231
4	0.1754 0.4233	1.0163 0.4209	0.1395 0.3369	0.9834 0.4073	0.1049 0.2532	0.9580 0.3689
5	0.1120 0.2931 0.3623	1.0116 0.6252 0	0.0895 0.2342 0.2895	0.9901 0.6119 0	0.0675 0.1766 0.2183	0.9735 0.6016 0

Table 2: Chebyshev Pole locations

n	C_1	L_2	C_3	L_4	C_5	L_6	C_7	L_8	R_2
2	0.8430	0.6220							0.7378
3	1.0315	1.1474	1.0315						1.0000
4	1.1087	1.3061	1.7703	0.8180					0.7378
5	1.1468	1.3712	1.9750	1.3712	1.1468				1.0000
6	1.1681	1.4039	2.0562	1.5170	2.9028	0.8618			0.7378
7	1.1811	1.4228	2.0966	1.5734	2.0966	1.4228	1.1811		1.0000
8	1.1897	1.4346	2.1199	1.6010	2.1699	1.5840	1.9444	0.8778	0.7378

Table 3: Low Pass Elements Value for LC ladder