Electrical Engineering Department
Delhi Technological University
(Formerly Delhi College of Engineering)
Bawana Road, Delhi – 110042

Certificate

I hereby certify that the Project Dissertation Titled "**Single OTRA based Inverse Filter Configuration**" which is submitted by Vishwajit Yadav, Roll No. : 2k22/C&I/09, Electrical Engineering Department, 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.

29/8/24

Prof. Ram Bhagat

Delhi Technological University
(Formerly Delhi College of Engineering)
Bawana Road, Delhi – 110042

Candidate's Declaration

I, Vishwajit Yadav, Roll No. : 2K22/C&I/09, Student of MTech (Control and Instrumentation), hereby declare that the project Dissertation Titled "**Single OTRA based Inverse Filter Configuration**" which is 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 for any degree, Diploma Associateship, Fellowship or other similar title or recognition.

Vishwajit.

Vishwajit Yadav

A
Dissertation
On

Single OTRA Based Inverse Filter Configuration

Submitted in Partial Fulfillment of the Requirements

For the Award of the Degree of

MASTER OF TECHNOLOGY

in

CONTROL AND INSTRUMENTATION ENGINEERING

Submitted By ;

Vishwajit Yadav
(Roll no. : 2K22/C&I/09)

Under the Supervision of ;

Prof. D.R. Bhaskar and Prof. Ram Bhagat

ELECTRICAL ENGINEERING DEPARTMENT
DELHI TECHNOLOGICAL UNIVERSITY
(FORMERLY DELHI COLLEGE OF ENGINEERING)
BAWANA ROAD, DELHI – 110042

(2024)

Delhi Technological University
(Formerly Delhi College of Engineering)
Bawana Road, Delhi – 110042

Candidate's Declaration

I, Vishwajit Yadav, Roll No. : 2K22/C&I/09, Student of MTech (Control and Instrumentation), hereby declare that the project Dissertation Titled "**Single OTRA based Inverse Filter Configuration**" which is 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 for any degree, Diploma Associateship, Fellowship or other similar title or recognition.

Vishwajit Yadav

Electrical Engineering Department
Delhi Technological University
(Formerly Delhi College of Engineering)
Bawana Road, Delhi – 110042

Certificate

I hereby certify that the Project Dissertation Titled "**Single OTRA based Inverse Filter Configuration**" which is submitted by Vishwajit Yadav, Roll No. : 2k22/C&I/09, Electrical Engineering Department, 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.

Prof. Ram Bhagat

ACKNOWLEDGEMENT

I take immense pleasure to express my deep and sincere gratitude to my esteemed supervisor, **Prof. D.R. Bhaskar**, for his invaluable guidance and spending of his precious hours for my work. His excellent cooperation and suggestion through stimulating and beneficial discussions provided me with an impetus to work and made the completion of work possible.

I also extend my sincere thanks to **Prof. Ram Bhagat** for offering invaluable assistance and helping me in my research work which boost up my confidence and pave the way to plan for surveying at the initial stages. He provided me constant encouragement and support in all possible ways.

I also appreciate and heartily thanks to all faculty member of **Department of Electrical Engineering** and all my lab mates for their constant support in my research work. I am also thankful to all my classmates and technical staff for supporting and helping me throughout the research work.

Finally, yet importantly, I would like to pay high regards to almighty Lord Krishna, my Parents, my family members and my friends for their real inspiration and motivation throughout my work and lifting me uphill this phase of life.

Vishwajit Yadav

ABSTRACT

A new OTRA-based multifunction inverse filter configuration is presented which is capable of realizing inverse low pass, inverse high pass, inverse band pass and inverse band reject filters using only one OTRA and five to six passive elements. To the best knowledge of the authors, any inverse filter configuration using OTRA has not been reported in the literature earlier. The proposed inverse filters are meticulously validated through simulations in Cadence PSpice, implemented in TSMC 0.18μm CMOS technology. The theoretical frequency response characteristics of all the proposed configurations match very well with the simulated ones. The proposed circuits are the only ones, which provide simultaneously the following features : use of reasonable number of active elements (only 1), realizability of all the four basic inverse filter functions, employment of all virtually grounded resistors and capacitors and tunability of all filter parameters (except gain in case of inverse band reject filter). The effect of the major parasitics of the OTRA and their effect on the performance of the filter have been investigated and measured through simulation results and Monte-Carlo analysis. Layout of the proposed CMOS OTRA has also been made using Layout XL Suite of Cadence Virtuoso using 180nm technology. Noise analysis as well as sensitivity analysis has also been studied.

TABLE OF CONTENTS

Candidate's Declaration	i
Certificate	ii
Acknowledgement	iii
Abstract	iv
CHAPTER 1 - INTRODUCTION	
1.1 Analog Signal Processing	1
1.2 Active Building Blocks (ABBs)	2
1.3 Organization of thesis	8
CHAPTER 2 - INVERSE ANALOG FILTERS	
2.1 Overview of Analog Inverse Filters	10
2.2 Literature Review	12
2.3 Objective and Scope of the Project	13
CHAPTER 3 - OPERATIONAL TRANSRESISTANCE AMPLIFIER (OTRA)	
3.1 Basics of OTRA	14
3.2 Single Pole Model of OTRA	14
3.3 Existing OTRA based inverse filter	15
CHAPTER 4 - PROPOSED CONFIGURATION	
4.1 Inverse Filter Configuration	19
4.2 Non-ideal Analysis	22
4.3 Error Analysis	24
4.4 Sensitivity analysis	25
CHAPTER 5 - SIMULATION RESULTS	
5.1 CMOS Realization of OTRA	26
5.2 Responses obtained	27
5.3 Noise Analysis	28
5.4 Monte carlo analysis	30
CHAPTER 6 - CONCLUSION AND FUTURE SCOPE	
6.1 Conclusion	32
6.2 Future Scope	32
REFERENCES	33

List Of Figures

Figure. 1.1 : Operational Amplifier

Figure. 1.2 :Operational Transconductance Amplifier

Figure. 1.3 : Current Feedback Opamp (CFOA)

Figure. 1.4 : Current Conveyor

Figure. 1.5 : Voltage Conveyor

Figure. 1.6 : Operational Transresistance Amplifier (OTRA)

Figure. 1.7 : Current Differencing Buffered Amplifier (CDBA)

Figure. 1.8 : Current Differencing Transconductance Amplifier (CDTA)

Figure. 1.9 : Voltage Differencing Transconductance Amplifier (VDTA)

Figure. 1.10 : Voltage Differencing Current Conveyor (VDCC)

Figure. 1.11 : Current Backward Transconductance Amplifier (CBTA)

Figure. 1.12 : Current Follower Current Conveyor (CFCC)

Figure. 1.13 : Current Follower Transconductance Amplifier (CFTA)

Figure. 1.14 : Current Conveyor Transconductance Amplifier (CCTA)

Figure. 1.15 : Multiple Output Current Follower Transconductance Amplifier (MO-CFTA)

Figure. 1.16 : Voltage Differencing Buffered Amplifier (VDBA)

Figure. 1.17 : Current Differencing Operational Amplifier (CDOA)

Figure. 1.18 : Differential Difference Current Conveyor (DDCC)

Figure. 2.1 : Response of ILPF

Figure. 2.2 : Response of IHPF

Figure. 2.3 : Response of IBPF

Figure. 2.4 : Response of IBRF

Figure. 3.1 : Representation of OTRA

Figure. 3.2 : Non-ideal structure of OTRA

Figure. 3.3 : Realization of Inverse Filters using two OTRA

Figure. 3.4 : Frequency response plot for ILPF

Figure. 3.5 : Frequency response plot for IHPF

Figure. 3.6 : Frequency response plot for IBPF

Figure. 4.1 : Proposed structure for realizing inverse filters

Figure. 5.1 : CMOS realization of OTRA

Figure. 5.2 : Layout of the OTRA

Figure. 5.3 : Frequency response plot for ILPF

Figure. 5.4 : Frequency response plot for IHPF

Figure. 5.5 : Frequency response plot for IBPF

Figure. 5.6 : Frequency response plot for IBRF

Figure. 5.7 : Noise Analysis for ILPF

Figure. 5.8 : Noise Analysis for IHPF

Figure. 5.9 : Noise Analysis for IBPF

Figure. 5.10 : Noise Analysis for IBRF

Figure. 5.11 : Monte Carlo analysis for inverse low pass filter

Figure. 5.12 : Monte Carlo analysis for inverse high pass filter

Figure. 5.13 : Monte Carlo analysis for inverse band pass filter

Figure. 5.14 : Monte Carlo analysis for inverse band reject filter

List of Tables

Table 4.1 : Error in value of gain for inverse filters

Table 4.2 : Sensitivity Analysis

Table 5.1 : W/L ratio of all transistors

Table 5.2 : Values of passive components

List of Abbreviations

CMOS : Complemetary Metal Oxide Semiconductor

ABB : Active Building Block

SPICE : Simulation Program with Integrated Circuit Emphasis

FTFN : Four Terminal Floating Nullor

Op-AMP : Operational Amplifier

OTA : Operational Transconductance Amplifier

CFOA : Current Feedback Operational Amplifier

CC : Current Conveyor

VC : Voltage Conveyor

OTRA : Operational Transresistance Amplifier

CDBA : Current Differencing Buffered Amplifier

CDTA : Current Differencing Transconductance Amplifier

VDTA : Voltage Differencing Transconductance Amplifier

VDCC : Voltage Differencing Current Conveyor

CBTA : Current Backward Transconductance Amplifier

CFCC : Current Follower Current Conveyor

CFTA : Current Follower Transconductance Amplifier

CCTA : Current Conveyor Transconductance Amplifier

MO-CFTA : Multiple Output Current Follower Transconductance Amplifier

VDBA : Voltage Differencing Buffered Amplifier

CDOA : Current Differencing Operational Amplifier

DDCC : Differential Difference Current Conveyor

ILPF : Inverse Low Pass Filter

IHPF : Inverse High Pass Filter

IBPF : Inverse Band Pass Filter

IBRF : Inverse Band Reject Filter

CHAPTER 1

INTRODUCTION

1.1 Analog Signal Processing

An electrical or electromagnetic current that spreads information between systems or networks is called a signal. A signal in electronics is often a time-varying voltage that also functions as an electromagnetic wave to transmit data, however signals can also be current. In electronics, two different types of signals are used: digital and analog. Time-varying and frequently restricted to a range (e.g., +12V to -12V), an analog signal can have an infinite number of values within its continuous range. An analog signal delivers information by utilizing a specific medium property, such as electricity passing across a wire. Information can be represented by changing the voltage, current, or frequency of an electrical signal. Analog signals are frequently calculated responses to changes in light, sound, temperature, position, pressure, or other physical phenomena.

The majority of essential electronic components—resistors, capacitors, inductors, diodes, transistors, and operational amplifiers (op amps)—are intrinsically analog. Analog circuits are created by combining these components. Analog circuits can be complicated with several components or simple, such as two resistors forming a voltage divider. In general, analog circuits are more complicated to build than digital circuits that provide the same function. An analog radio receiver or an analog battery charger would require the expertise of an analog circuit designer, while digital components have been used to simplify such designs. Analog circuits are more vulnerable to noise, which is defined as any minor, undesirable voltage changes. Small variations in the voltage level of an analog signal might result in severe mistakes when processed.

Analog signal processing is a sort of signal processing performed on continuous analog signals using analog means (as opposed to discrete digital signal processing, which uses a digital process). "Analog" refers to something that is mathematically expressed as a collection of continuous values.

1.2 Active Building Blocks (ABBs)

Various authors have presented circuit realizations of inverse filters using different Active Building Blocks (ABB) such as :-

Operational Amplifier (OpAmp) **[1]**

It is a Voltage Controlled Voltage Source, with ideally, infinite gain, infinite input impedance and zero output impedance. Its terminal equation is given by ;

$$V_+ = V_- \ , \ I_+ = I_- = 0 \ , \ V_{OUT} = A_v (V_+ - V_-) \ ; \ \{A_v : \text{Voltage Gain}\} \qquad 1.1$$

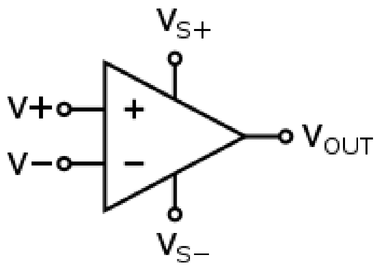

Fig. 1.1. Operational Amplifier [1]

Operational Transconductance Amplifier (OTA) **[2]**

It is a Voltage Controlled Current Source, with ideally, infinite input impedance and infinite output impedance.

$$I_o = g_m (V_1 - V_2) \ ; \ \{g_m : \text{Transconductance Gain}\} \qquad 1.2$$

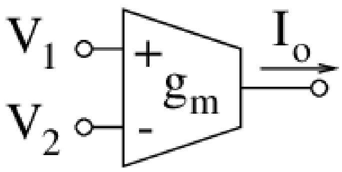

Fig. 1.2. Operational Transconductance Amplifier [2]

Current Feedback OpAmp (CFOA) **[3]**

This element is constructed by using the second generation current conveyor and voltage buffer.

It is a four port network described by the following equations ;

$$I_Y = 0 \ , \ I_Z = I_X \ , \ V_X = V_Y \ , \ V_o = V_Z \qquad 1.3$$

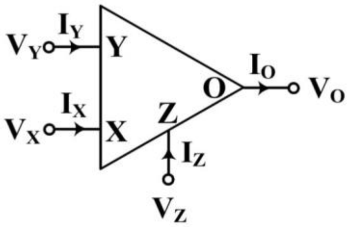

Fig. 1.3. Current Feedback Opamp (CFOA) [3]

Current Conveyor (CCII) **[4]**

It is a three port device represented by the following equations ;

$$I_Y = 0 , V_X = V_Y , I_Z = \pm I_X \tag{1.4}$$

In CCII, Y is high-impedance voltage input port and X is low-impedance voltage output port.

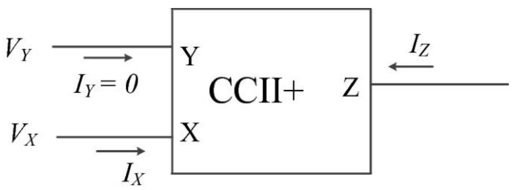

Fig. 1.4. Current Conveyor [4]

Voltage Conveyor (VCII) **[5]**

In the VCII, Y is a low-impedance current input port and X is a high-impedance current output port.

$$I_X = \pm I_Y , V_Z = V_X , V_Y = 0 \tag{1.5}$$

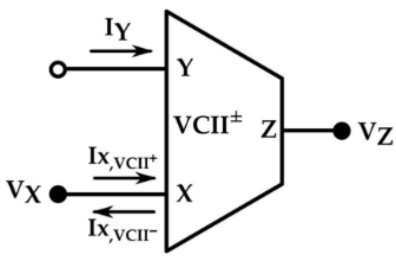

Fig. 1.5. Voltage Conveyor [5]

Operational Transresistance Amplifier (OTRA) **[6]**

An OTRA is a current-controlled voltage source with three terminals as shown below ;

$$V_p = V_n = 0 , V_o = R_m (I_p - I_n) ; \{R_m : \text{Transresistance Gain}\} \tag{1.6}$$

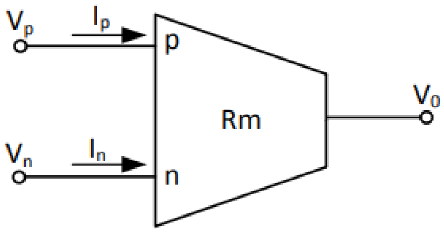

Fig. 1.6. Operational Transresistance Amplifier (OTRA) [6]

Current Differencing Buffered Amplifier (CDBA) **[7]**

It is a four terminal device depicted as follows ;

$$V_p = V_n = 0 \text{ , } I_z = I_p - I_n \text{ , } V_w = V_z \qquad 1.7$$

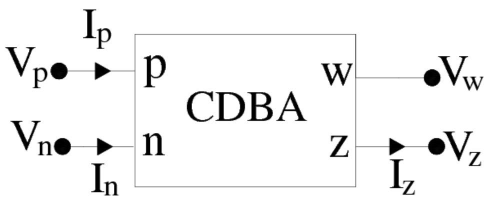

Fig. 1.7. Current Differencing Buffered Amplifier (CDBA) [7]

Current Differencing Transconductance Amplifier (CDTA) **[8]**

It is a five terminal device as shown below ;

$$I_z = - I_n \text{ , } I_{x+} = g.V_z \text{ , } I_{x-} = -g.V_z \text{ , } V_p = V_n = 0 \text{ ; } \{g : \text{transconductance}\} \qquad 1.8$$

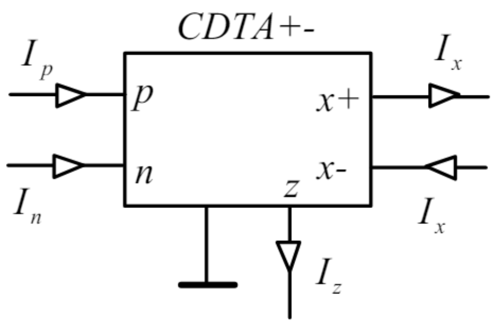

Fig. 1.8. Current Differencing Transconductance Amplifier (CDTA) [8]

Voltage Differencing Transconductance Amplifier (VDTA) **[9]**

It is also a five terminal device as shown below ;

$$I_z = g_{m1}.(V_p - V_n) \text{ , } I_{x+} = g_{m2}.V_z \text{ , } I_{x-} = -g_{m2}.V_z \qquad 1.9$$

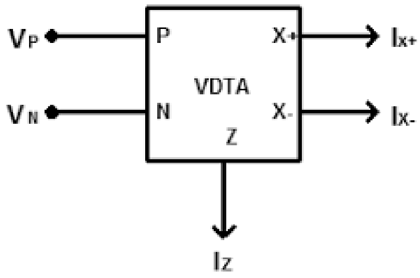

Fig. 1.9. Voltage Differencing Transconductance Amplifier (VDTA) [9]

Voltage Differencing Current Conveyor (VDCC) **[10]**

It is a six terminal device as shown below ;

$$I_p = I_n = 0 \,,\ I_z = g_m (V_p - V_n) \,,\ V_x = V_z \,,\ I_{wp} = I_x \,,\ I_{wn} = -I_x \qquad 1.10$$

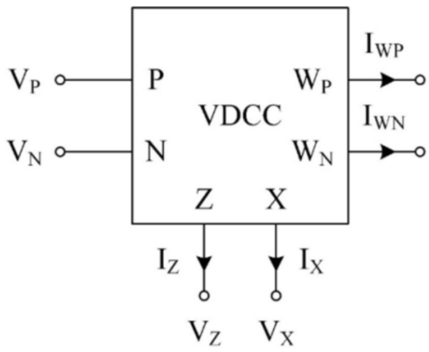

Fig. 1.10. Voltage Differencing Current Conveyor (VDCC) [10]

Current Backward Transconductance Amplifier (CBTA) **[11]**

The ideal terminal voltage-current equations of the CBTA can be defined as ;

$$I_z = g_m.(V_p - V_n) \,,\ V_w = V_z \,,\ I_p = I_w \,,\ I_n = -I_w \qquad 1.11$$

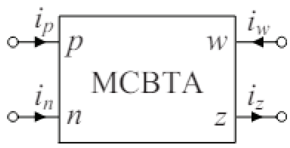

Fig. 1.11. Current Backward Transconductance Amplifier (CBTA) [11]

Current Follower Current Conveyor (CFCC) **[12]**

It is a four terminal device as shown below ;

$$V_p = 0 \,,\ I_z = I_p \,,\ V_i = V_z \,,\ I_{x+} = I_i \,,\ I_{x-} = -I_i \qquad 1.12$$

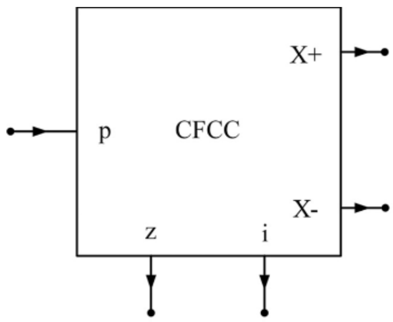

Fig. 1.12. Current Follower Current Conveyor (CFCC) [12]

<u>Current Follower Transconductance Amplifier (CFTA)</u> **[13]**

The current follower transconductance amplifier (CFTA) is a current mode active block. It is a combination of current follower (CF) and operational transconductance amplifier (OTA) at the output stage.

$$V_f = 0,\ I_z,\ \pm Z_c = \pm I_f,\ I_o = g_m.V_z \qquad 1.13$$

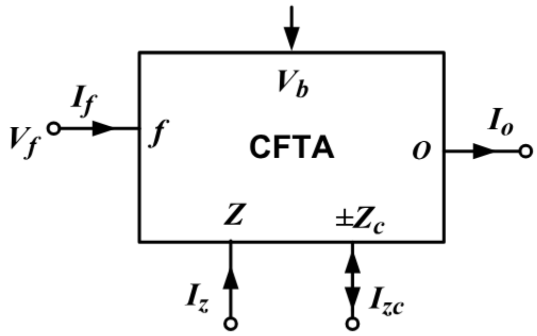

Fig. 1.13. Current Follower Transconductance Amplifier (CFTA) [13]

<u>Current Conveyor Transconductance Amplifier (CCTA)</u> **[14]**

It is a five terminal device represented as follows ;

$$I_p = I_n,\ V_p = V_n,\ I_z = I_n,\ I_{x+} = -I_{x-} = g_m.V_z \qquad 1.14$$

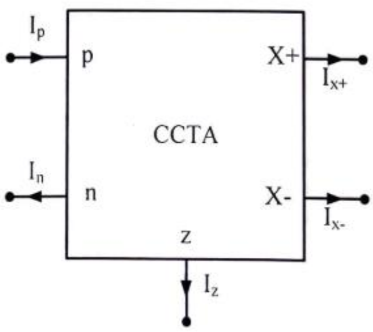

Fig. 1.14. Current Conveyor Transconductance Amplifier (CCTA) [14]

Multiple Output Current Follower Transconductance Amplifier (MO-CFTA) **[15]**

A MO-CFTA is a combination of current follower and multioutput transconductance amplifier. The properties of ideal MOCFTA can be characterized by the following set of equations;

$$V_f = 0 \, , \, I_z = \pm I_f \, , \, I_x = \pm g_m V_z \quad 1.15$$

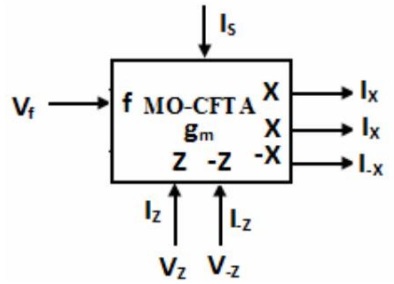

Fig. 1.15. Multiple Output Current Follower Transconductance Amplifier (MO-CFTA) [15]

Voltage Differencing Buffered Amplifier (VDBA) **[16]**

VDBA has a pair of high-impedance voltage inputs V_p and V_n, high-impedance current outputs I_z, I_{zc-} and low-impedance voltage output V_w. It is represented as follows ;

$$I_p = I_n = 0 \, , \, I_z = g_m(V_p - V_n) \, , \, I_{zc-} = g_m(V_n - V_p) \, , \, V_w = V_z \quad 1.16$$

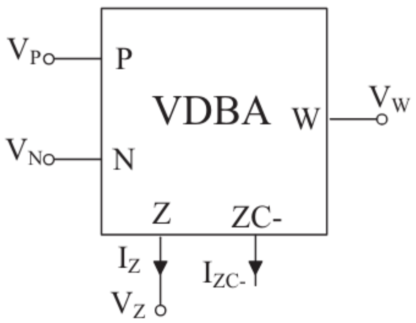

Fig. 1.16. Voltage Differencing Buffered Amplifier (VDBA) [16]

Current Differencing Operational Amplifier (CDOA) **[17]**

The current differencing operational amplifier is five terminal active circuit and terminal characteristics are described as follows ;

$$V_p = V_n = 0 \, , \, I_z = I_p - I_n \, , \, V_w = V_z - V_v \quad 1.17$$

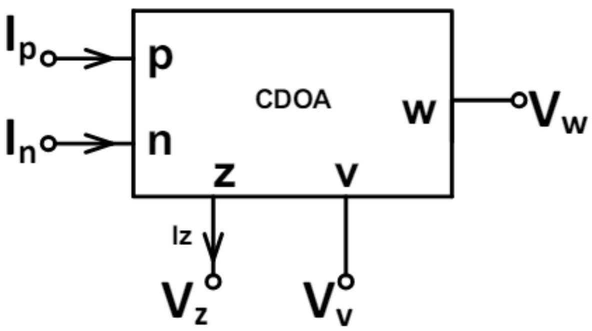

Fig. 1.17. Current Differencing Operational Amplifier (CDOA) [17]

<u>Differential Difference Current Conveyor (DDCC)</u> **[18]**

It is shown as follows ;

$$I_{Y1} = I_{Y2} = I_{Y3} = 0\ ,\ V_x = \beta_1 V_{Y1} - \beta_2 V_{Y2} + \beta_3 V_{Y3}\ ,\ I_z = \alpha I_x \qquad 1.18$$

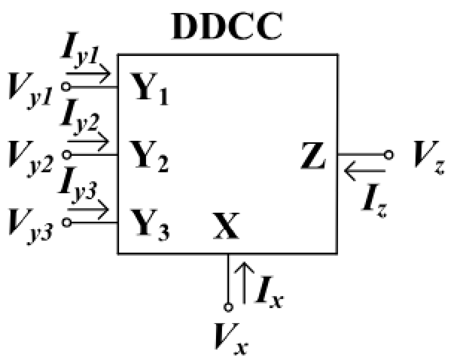

Fig. 1.18. Differential Difference Current Conveyor (DDCC) [18]

1.3 Organization of thesis

The thesis is organized as follows ;

Chapter 2 : It gives a detailed overview of Inverse Analog Filters along with the literature review of the existing inverse filters.

Chapter 3 : It describes the basics of the OTRA, its non-ideal model taking parasitic into account and an existing configuration of inverse filter employing two OTRA.

Chapter 4 : Here, a circuit is proposed using single OTRA along with few passive components that can realize all four inverse filters, i.e., ILPF, IHPF, IBPF and IBRF. Parameters like cutoff frequency, quality factor, gain and bandwidth are also found out using the transfer functions of the respective inverse filter. The non-ideal analysis has been carried out along with the calculation of percentage error in the value of gain. The Sensitivity analysis has also been performed.

Chapter 5 : This chapter presents the simulation results (ideal, simulated and non-ideal responses), along with the noise analysis and monte carlo analysis for all four inverse filters.

Chapter 6 : In this section conclusion of the thesis work and future scope of the work are presented.

CHAPTER 2

INVERSE ANALOG FILTERS

2.1 Overview of Analog Inverse Filters

Over the last three decades, there has been substantial attention focused on the circuit realizations of analog inverse filters (AIF). Since the frequency-selective properties of an analog inverse filter are the reverse of those of conventional analog filters, its goal is to reduce the distortion that a signal experiences as it traverses a system [19] and hence they find their application in communication, instrumentation and control systems. The meaning of the coefficients such as gain (H_o) , cutoff frequency (ω_0) , quality factor (Q) and bandwidth (ω_o/Q) is clear in context with the conventional filters. These coefficients have the same meaning in context with inverse filters too.

The inverse low pass filter (ILPF) can be depicted as follows :-

$$(TF)_{ILPF} = \frac{s^2 + s\left(\frac{\omega_o}{Q}\right) + \omega_o^2}{H_o \omega_o^2} \qquad 2.1$$

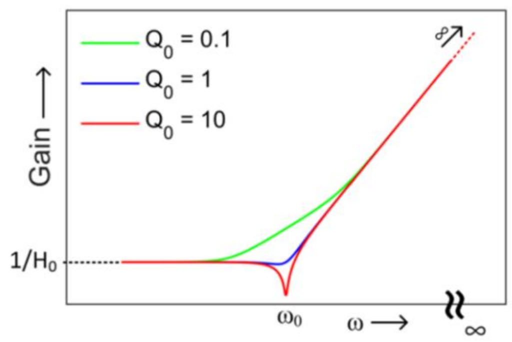

Fig. 2.1. Response of ILPF [49]

The inverse high pass filter (IHPF) can be depicted as follows :-

$$(TF)_{IHPF} = \frac{s^2 + s\left(\frac{\omega_o}{Q}\right) + \omega_o^2}{H_o s^2} \qquad 2.2$$

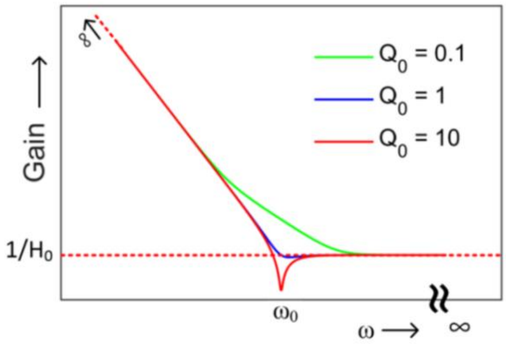

Fig. 2.2. Response of IHPF [49]

The inverse band pass filter (IBPF) can be depicted as follows :-

$$(TF)_{IBPF} = \frac{s^2 + s\left(\frac{\omega_o}{Q}\right) + \omega_o^2}{H_o s\left(\frac{\omega_o}{Q}\right)} \qquad 2.3$$

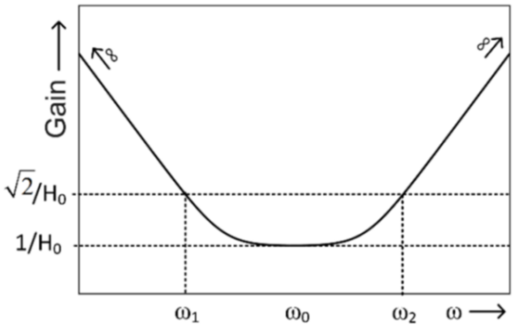

Fig. 2.3. Response of IBPF [49]

The inverse band reject filter (IBRF) can be depicted as follows :-

$$(TF)_{IBRF} = \frac{s^2 + s\left(\frac{\omega_o}{Q}\right) + \omega_o^2}{H_o(s^2 + \omega_o^2)} \qquad 2.4$$

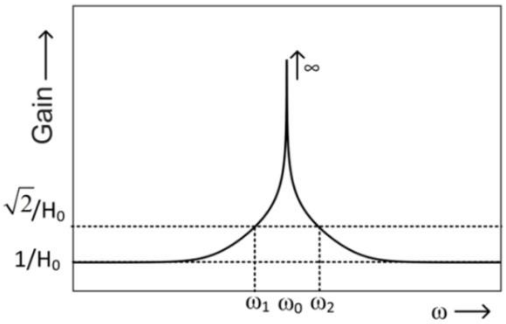

Fig. 2.4. Response of IBRF [49]

The inverse all pass filter (IAPF) can be depicted as follows :-

$$(\mathrm{TF})_{\mathrm{IAPF}} = \frac{s^2 + s\left(\frac{\omega_o}{Q}\right) + \omega_o^2}{s^2 - s\left(\frac{\omega_o}{Q}\right) + \omega_o^2} \qquad 2.5$$

2.2 Literature Review

In the open literature, numerous inverse filter designs employing different active devices have been presented over the years [20]-[50], out of which [20]-[30] summarizes the inverse filter configurations using only one Active Building Block (ABB).

In [20], Kamat presented an inverse filter construction based on operational amplifier that can accomplish inverse band pass filtering at the second order as well as inverse low pass filtering and inverse high pass filtering at the first order, with the least amount of passive components. In [21], Shah demonstrated a voltage mode CCII (Current Conveyor) based multifunction first order all pass filter, as well as its inverted counterpart, which uses one grounded capacitor and two resistors. In [22], Chipipop and Surakampontorn presented a circuit that is able to implement second order inverse low pass filter using Four Terminal Floating Nullor (FTFN) whereas in [23], Wang and Lee presented a procedure for realizing second order inverse all pass filter using FTFN. In [24], five configurations are presented that can realize current mode second order inverse filter responses i.e. ILPF, IHPF, IBPF, IBRF and IAPF using FTFN and in [25], Shah and Malik introduced current mode inverse all pass filter of first order based on FTFN. In [26], Singh and Prasad introduced filter/inverse filter circuits using single FTFN. In [27], the Operational Transresistance Amplifier (OTRA) is used to introduce three alternative configurations of inverse band reject filter of second order. In [28], Paul, Roy, and Pal demonstrated a CDBA-based setup that can achieve second-order ILPF, IHPF, IBPF, and IBRF. In [29], Shah, Iqbal, and Quadri introduced first order inverse all pass filter based on Current Differencing Transconductance Amplifier (CDTA) with a grounded capacitor and a resistor. In [30], single VCII (voltage conveyor) based configuration is presented capable of realizing ILPF, IHPF and IBPF.

In [31], Tsukutani, Sumi and Yabuki presented current mode as well as voltage mode electronically tunable inverse filters using and grounded capacitors whereas in [32], Raj, Bhagat, Kumar and Bhaskar presented electronically tunable voltage mode inverse filters using OTAs and grounded capacitors. In [33-34], Gupta, Bhaskar and Senani presented based analog inverse. In [35], Wang, Chang, Yang and Tsai presented an inverse filter configuration that is capable to realize second order ILPF, IHPF and IBPF employing three CFOAs along with few admittances. In [36], Garg, Bhagat and Jaint presented a modified inverse filter structure that can realize second order voltage mode ILPF, IHPF and IBPF using three CFOAs. In [37], Patil and Sharma introduced CFOA based circuit that is capable of realizing ILPF, IHPF, IBPF and IBRF responses. In [38], Singh, Gupta and Senani presented a configuration that can realize ILPF, IHPF and IBPF using two OTRAs and few passive components whereas in [39], Pradhan and Sharma presented two configurations using OTRAs that can realize various IAPFs and IBRFs using different combinations of the passive components. In [40], second order voltage mode ILPF, IHPF and IBPF is presented employing two CDBAs. In [41], Nasir and Ahmad defined a procedure to realize current mode ILPF, IHPF and IBPF responses using CDBA. In [42], Bhagat, Bhaskar and Kumar introduced CDBA based circuit to realize second order IBRF and IAPF. In [43], Bhagat, Bhaskar and Kumar presented a unique CDBA based configuration capable of realizing second order LPF, HPF, BPF and their respective inverse responses. In [44], Borah, Singh and Ghosh realized a sixth order IBPF using two CDBAs. In [45], Kumar, Pandey and Paul realized electrically tunable inverse filters using VDTA and in [46], Kumar, Pandey and Paul presented a configuration consisting of four VDTAs along with two grounded capacitors capable of realizing ILPF, IHPF, IBPF and IBRF in voltage mode. In [47], Al-Absi presented three configurations for realizing ILPF, IHPF and IBPF using two to three VCII+ as active building blocks along with few passive components. In [48], Al-Shahrani and Al-Absi disclosed four configurations capable of realizing ILPF, IHPF, IBPF and IBRF using VCII+. In [49], Senani, Bhaskar and Raj presented a detailed review of analog inverse filters using various active building blocks along with an unresolved issue of realizing PID control using IBPF. In [50], Nako, Psychalinos and Minaei defined a procedure to realize inverse filters with cascade capability.

2.3 Objective and Scope of the Project

This thesis describes a novel inverse filter design based on a single OTRA, using two/three resistors and two/three capacitors. The proposed inverse filters are meticulously validated through simulations in Cadence PSpice, implemented in CMOS TSMC 0.18µm technology.

CHAPTER 3

OPERATIONAL TRANSRESISTANCE AMPLIFIER (OTRA)

3.1 Basics of OTRA

An OTRA is current controlled voltage source which is a three terminal device as shown in Fig. 3.1, represented by equation (3.1) and matrix form as shown in (3.2).

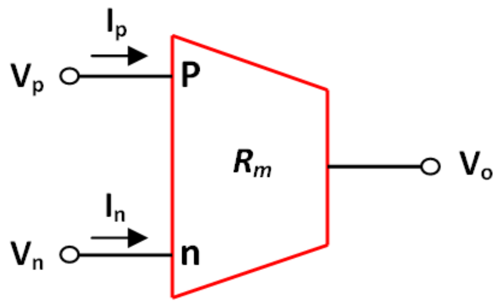

Fig. 3.1. Representation of OTRA

$$V_o = R_m\,(I_p - I_n) \tag{3.1}$$

$$\begin{bmatrix} V_p \\ V_n \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ R_m & -R_m & 0 \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ I_o \end{bmatrix} \tag{3.2}$$

In ideal conditions, R_m (transresistance gain) is assumed to be infinite so the currents I_p and I_n [52] becomes equal. All the three terminals of OTRA have low impedance. Low output impedance makes it easier to be cascaded. Virtually shorted input terminals eliminates parasitic components at both of its inputs [51].

3.2 Single Pole Model of OTRA

In the ideal scenario, the trans-resistance gain 'R_m' of an OTRA is very high and can be assumed to be infinite and hence the two input current becomes equal. However, in practical case, the transresistance gain 'R_m' is considered as a very high but finite value and hence it has considerable effect. The single pole model of the OTRA is represented as follows ;

$$R_m(s) = \frac{R_p}{1+\frac{s}{w_o}} = \frac{R_p w_o}{s+w_o} = \frac{1}{\frac{s}{R_p w_o}+\frac{1}{R_p}} \quad 3.3$$

The non-ideal structure of OTRA is shown in Fig. 3.2;

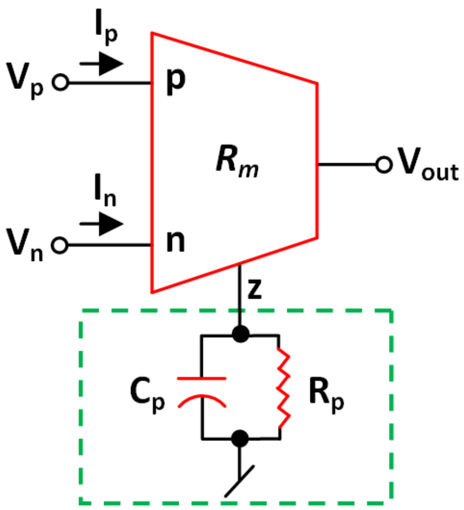

Fig. 3.2. Non-ideal structure of OTRA

The approximated model for transresistance gain, $R_m(s)$, for middle/higher frequencies is shown in equation (3.4).

$$R_p \rightarrow \infty ,\ R_m(s) \approx \frac{1}{sC_p} \quad 3.4$$

Where ;

$$C_p = \frac{1}{w_o R_p} \quad 3.5$$

R_p (parasitic resistance) is the open-loop transresistance gain, w_o is the cut-off frequency and C_p is the parasitic capacitance.

3.3 Existing OTRA based inverse filter

The work of Singh, Gupta and Senani [38], conveyed that the inverse filter responses, i.e., ILPF , IHPF and IBPF can be achieved using two OTRA along with few passive components, at a frequency of 159kHz. This is shown as follows :-

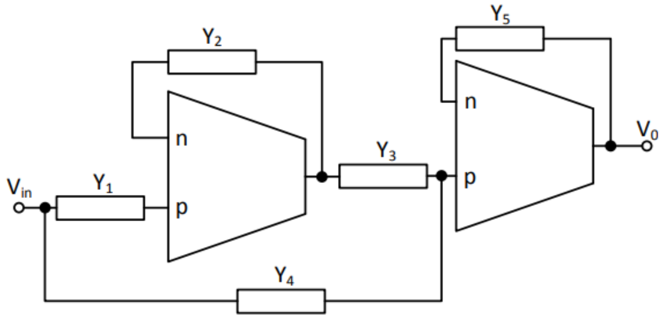

Fig. 3.3. Realization of Inverse Filters using two OTRA [38]

Transfer Function is given as ;

$$\frac{V_o}{V_{in}} = \frac{Y_1Y_3+Y_2Y_4}{Y_2Y_5} \qquad 3.6$$

If $Y_1 = sC_1$, $Y_2 = \frac{1}{R_2}$, $Y_3 = sC_2 + \frac{1}{R_3}$, $Y_4 = \frac{1}{R_4}$, $Y_5 = \frac{1}{R_5}$, the transfer function for ILPF is obtained as follows ;

$$\frac{V_o(s)}{V_{in}(s)} = \frac{s^2 + s\left(\frac{1}{R_3C_2}\right) + \frac{1}{R_2C_1R_4C_2}}{\left(\frac{R_4}{R_5}\right)\left(\frac{1}{R_2C_1R_4C_2}\right)} \qquad 3.7$$

Where ;

$$(w_0)_{ILPF} = \frac{1}{\sqrt{R_2C_1R_4C_2}}$$
$$(H_o)_{ILPF} = \frac{R_4}{R_5} \qquad 3.8$$
$$(Q)_{ILPF} = \frac{R_3\sqrt{C_2}}{\sqrt{R_2C_1R_4}}$$

If $Y_1 = \frac{1}{R_1}$, $Y_2 = sC_2$, $Y_3 = \frac{1}{R_3}$, $Y_4 = sC_4 + \frac{1}{R_4}$, $Y_5 = sC_5$, the transfer function for IHPF is obtained as follows ;

$$\frac{V_o(s)}{V_{in}(s)} = \frac{s^2 + s\left(\frac{1}{R_4C_4}\right) + \frac{1}{R_1C_4R_3C_2}}{s^2} \qquad 3.9$$

Where ;

$$(w_0)_{IHPF} = \frac{1}{\sqrt{R_4R_2C_1C_2}}$$
$$(H_o)_{IHPF} = 1 \qquad 3.10$$
$$(Q)_{IHPF} = \frac{R_3\sqrt{C_2}}{\sqrt{R_2C_1R_4}}$$

If $Y_1 = \frac{1}{R_1}$, $Y_2 = sC_2$, $Y_3 = \frac{1}{R_3}$, $Y_4 = sC_4 + \frac{1}{R_4}$, $Y_5 = \frac{1}{R_5}$, the transfer function for IBPF is obtained as follows ;

$$\frac{V_o(s)}{V_{in}(s)} = \frac{s^2 + s\left(\frac{1}{R_4C_4}\right) + \frac{1}{R_1C_4R_3C_2}}{\left(\frac{R_4}{R_5}\right)s\left(\frac{1}{R_4C_4}\right)} \tag{3.11}$$

Where ;

$$(w_0)_{IBPF} = \frac{1}{\sqrt{R_1C_4R_3C_2}}$$
$$(BW)_{IBPF} = \frac{1}{R_4C_4} \tag{3.12}$$
$$(H_o)_{IBPF} = \frac{R_4}{R_5}$$

The Responses obtained are as follows ;

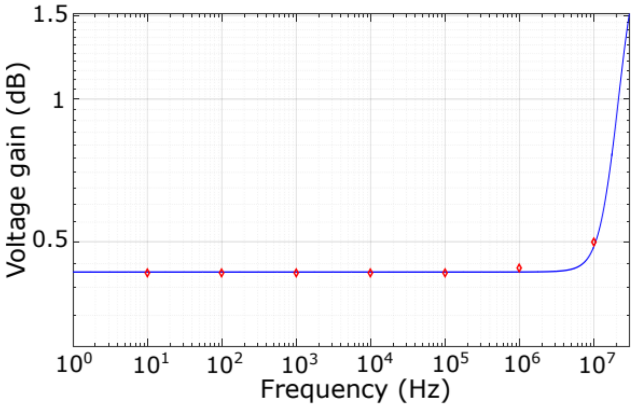

Fig. 3.4. Frequency response plot for ILPF [38]

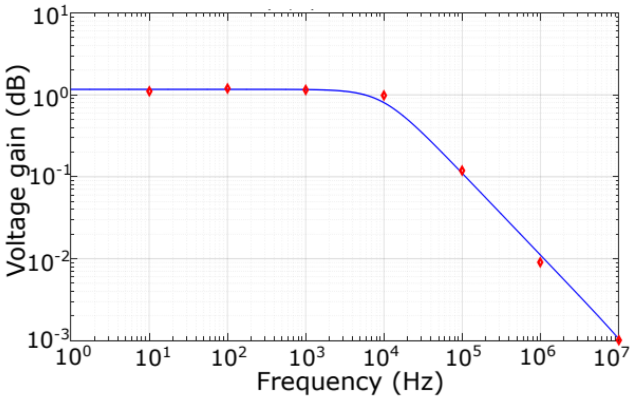

Fig. 3.5. Frequency response plot for IHPF [38]

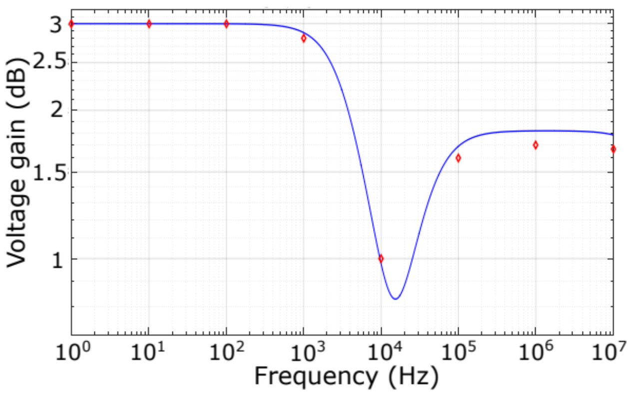

Fig. 3.6. Frequency response plot for IBPF [38]

Conclusion :-

Thus, this configuration, employing of two OTRA, is capable of ILPF, IHPF and IBPF along with the use of few admittances. Simulations of the three inverse filters were performed using the CMOS OTRA model to verify their performance. Additional validation is performed using non-ideal analysis and Monte Carlo analysis.

CHAPTER 4

PROPOSED CONFIGURATION

4.1 Inverse Filter Configuration

The proposed configuration for realizing inverse low pass filter (ILPF), inverse high pass filter (IHPF), inverse band pass filter (IBPF) and inverse band reject filter (IBRF) using a single device OTRA and three impedances is shown in Fig. 4.1.

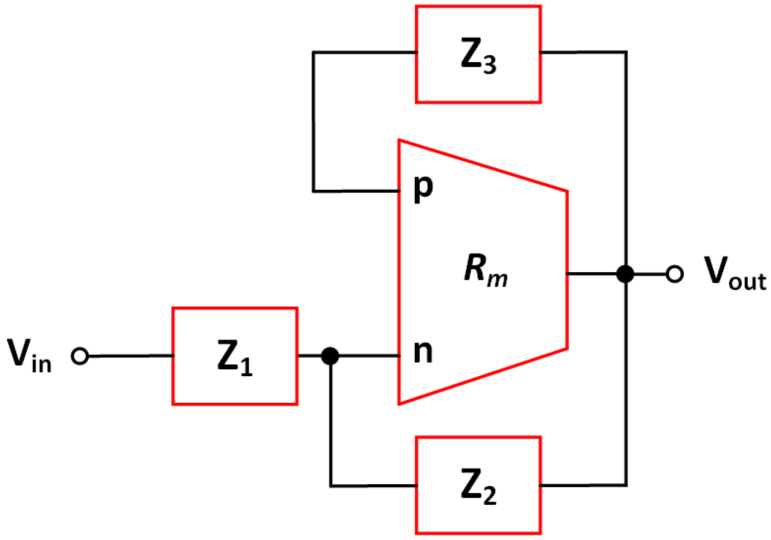

Fig. 4.1. Proposed structure for realizing inverse filters

In contrast with the previously published configuration [38], the proposed structure utilizes one OTRA as the only active element along with a reduced number of passive components. In addition to ILPF, IHPF and IBPF, the proposed structure can also realize IBRF response which was not possible in the former case.

Assuming ideal OTRA, a routine circuit analysis of Fig. 4.1 yields the following transfer function (TF);

$$\frac{Vout}{Vin} = \frac{Z_2 Z_3}{Z_1(Z_2 - Z_3)} \quad (4.1)$$

<u>Case 1</u> :-

Taking $Z_1 = R_1 \| \frac{1}{sC_1}$, $Z_2 = R_2$, $Z_3 = R_3 + \frac{1}{sC_3}$, transfer function becomes :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{[s^2 R_1 C_1 R_3 C_3 + s(R_1 C_1 + R_3 C_3) + 1]}{\left(\frac{R_1}{R_2}\right)(sR_3 C_2 - sC_3 R_3 + 1)} \qquad 4.2$$

Assuming $R_2 = R_3$ in equation (4.2), to obtain the transfer function of **ILPF**:-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{s^2 + s\left(\frac{R_1 C_1 + R_3 C_3}{R_1 C_1 R_3 C_3}\right) + \left(\frac{1}{R_1 C_1 R_3 C_3}\right)}{\left(\frac{R_1}{R_2}\right)\left(\frac{1}{R_1 C_1 R_3 C_3}\right)} \qquad 4.3$$

From equation (4.3), the cutoff frequency $(w_0)_{ILPF}$, quality factor $(Q)_{ILPF}$ and gain $(H_o)_{ILPF}$ are given by;

$$(w_0)_{ILPF} = \frac{1}{\sqrt{R_1 R_3 C_1 C_3}}$$

$$(H_o)_{ILPF} = \frac{R_1}{R_2} \qquad 4.4$$

$$(Q)_{ILPF} = \frac{\sqrt{R_1 R_3 C_1 C_3}}{R_1 C_1 + R_3 C_3}$$

<u>Case 2</u> :-

Taking $Z_1 = R_1 \| \frac{1}{sC_1}$, $Z_2 = R_2 + \frac{1}{sC_2}$, $Z_3 = \frac{1}{sC_3}$, transfer function becomes :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{[s^2 R_1 C_1 R_2 C_2 + s(R_1 C_1 + R_2 C_2) + 1]}{R_1(S^2 C_2 R_2 C_3 + SC_3 - SC_2)} \qquad 4.5$$

Assuming $C_2 = C_3$ in equation (4.5), to obtain the transfer function of **IHPF** :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{s^2 + s\left(\frac{R_1 C_1 + R_2 C_2}{R_1 C_1 R_2 C_2}\right) + \left(\frac{1}{R_1 C_1 R_2 C_2}\right)}{s^2 (C_3 / C_1)} \qquad 4.6$$

From equation (4.6), the cutoff frequency $(w_0)_{IHPF}$, quality factor $(Q)_{IHPF}$ and gain $(H_o)_{IHPF}$ are given by;

$$(w_0)_{IHPF} = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

$$(H_o)_{IHPF} = \frac{C_3}{C_1} \qquad 4.7$$

$$(Q)_{IHPF} = \frac{\sqrt{R_1 R_2 C_1 C_2}}{R_1 C_1 + R_2 C_2}$$

<u>Case 3</u> :-

Taking $Z_1 = R_1$, $Z_2 = R_2 + \frac{1}{sC_2}$, $Z_3 = R_3 + \frac{1}{sC_3}$, transfer function becomes :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{[s^2R_3C_3R_2C_2 + s(R_3C_3+R_2C_2) + 1]}{R_1(s^2C_3R_2C_2 - s^2C_2R_3C_3 + sC_3 - sC_2)} \quad 4.8$$

Assuming $R_2 = R_3$ in equation (4.8), to obtain the transfer function of **IBPF**:-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{s^2 + s\left(\frac{R_2C_2+R_3C_3}{R_2C_2R_3C_3}\right) + \left(\frac{1}{R_2C_2R_3C_3}\right)}{sR_1\left(\frac{C_3-C_2}{R_2C_2+R_3C_3}\right)\left(\frac{R_2C_2+R_3C_3}{R_2C_2R_3C_3}\right)} \quad 4.9$$

From equation (4.9), the centre frequency $(w_0)_{IBPF}$, bandwidth $(BW)_{IBPF}$ and gain $(H_o)_{IBPF}$ are given by;

$$(w_0)_{IBPF} = \frac{1}{\sqrt{R_3R_2C_3C_2}}$$
$$(BW)_{IBPF} = \frac{R_3C_3+R_2C_2}{R_3C_3R_2C_2} \quad 4.10$$
$$(H_o)_{IBPF} = \frac{R_1(C_3-C_2)}{R_2C_2+R_3C_3}$$

<u>Case 4</u> :-

Taking $Z_1 = R_1 \| \frac{1}{sC_1}$, $Z_2 = R_2 \| \frac{1}{sC_2}$, $Z_3 = R_3 + \frac{1}{sC_3}$, transfer function becomes :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{[s^2R_1C_1R_3C_3 + s(R_1C_1+R_3C_3) + 1]}{\left(\frac{R_1}{R_2}\right)(S^2R_3R_2C_3C_2 + SR_3C_3 + SR_2C_2 - SR_2C_3 + 1)} \quad 4.11$$

Assuming $C_1 = C_3 = 2C_2$ and $R_2 = 2R_3 = 2R_1$ in equation (4.11), to obtain the transfer function of **IBRF** :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{s^2 + s\left(\frac{2}{R_3C_3}\right) + \frac{1}{R_3^2C_3^2}}{\left(\frac{1}{2}\right)\left(S^2 + \frac{1}{R_3^2C_3^2}\right)} \quad 4.12$$

From equation (4.12), the centre frequency $(w_0)_{IBRF}$, bandwidth $(BW)_{IBRF}$ and gain $(H_o)_{IBRF}$ are given by;

$$(w_0)_{IBRF} = \frac{1}{R_3C_3}$$
$$(BW)_{IBRF} = \frac{2}{R_3C_3} \quad 4.13$$
$$(H_o)_{IBRF} = \frac{C_2}{C_1} = \frac{1}{2}$$

4.2 Non-ideal Analysis

The non-ideal transfer function is as shown in equation (4.14), taking the effect of parasitic into account using single pole model of OTRA.

$$\frac{V_o}{V_{in}} = \frac{Z_2 Z_3}{Z_1\left(Z_2 - Z_3 - \frac{Z_2 Z_3}{R_m}\right)} \qquad 4.14$$

Using above transfer function, the non-ideal transfer functions obtained for ILPF, IHPF, IBPF, and IBRF are presented below.

Case 1 :-

Putting $Z_1 = R_1 \| \frac{1}{sC_1}$, $Z_2 = R_2$, $Z_3 = R_3 + \frac{1}{sC_3}$, to get the following transfer function for ILPF :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{\left(\frac{R_2 R_p}{R_1}\right)[s^2 R_1 C_1 R_3 C_3 + s(R_1 C_1 + R_3 C_3) + 1]}{\left[s^2 R_p C_P R_2 R_3 C_3 + (R_2 + R_p) + s\left(C_P R_p R_2 + R_2 R_3 C_3 - R_2 R_p C_3 + R_p R_3 C_3\right)\right]} \qquad 4.15$$

Equation (4.15) can be approximated to obtain **ILPF** :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{s^2 + s\left(\frac{R_1 C_1 + R_3 C_3}{R_1 C_1 R_3 C_3}\right) + \left(\frac{1}{R_1 C_1 R_3 C_3}\right)}{\left[1 + \frac{R_2}{R_p}\right]\left(\frac{R_1}{R_2}\right)\left(\frac{1}{R_1 C_1 R_3 C_3}\right)} \qquad 4.16$$

From equation (4.16), cutoff frequency $(\widetilde{w}_0)_{ILPF}$, quality factor $(\widetilde{Q})_{ILPF}$ and gain $(\widetilde{H}_o)_{ILPF}$ are given by;

$$(\widetilde{w}_0)_{ILPF} = \frac{1}{\sqrt{R_1 R_3 C_1 C_3}}$$
$$(\widetilde{Q})_{ILPF} = \frac{\sqrt{R_1 R_3 C_1 C_3}}{R_1 C_1 + R_3 C_3} \qquad 4.17$$
$$(\widetilde{H}_o)_{ILPF} = \left[\frac{R_2 + R_p}{R_p}\right]\left(\frac{R_1}{R_2}\right)$$

Case 2 :-

Taking $Z_1 = R_1 \| \frac{1}{sC_1}$, $Z_2 = R_2 + \frac{1}{sC_2}$, $Z_3 = \frac{1}{sC_3}$, transfer function becomes :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{R_p[s^2 R_1 R_2 C_1 C_2 + s(R_1 C_1 + R_2 C_2) + 1]}{R_1\left[s^2 R_p R_2 C_2 (C_3 - C_P) + s\left(C_3 R_p - C_2 R_p - C_2 R_2 - R_p C_p\right) - 1\right]} \qquad 4.18$$

Equation (4.18) can be approximated to obtain **IHPF** :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{s^2 + s\left(\frac{R_1C_1+R_2C_2}{R_1C_1R_2C_2}\right) + \left(\frac{1}{R_1C_1R_2C_2}\right)}{s^2\left[\frac{C_3-C_p}{C_1}\right]} \qquad 4.19$$

From equation (4.19), cutoff frequency $(\widetilde{w}_0)_{IHPF}$, quality factor $(\widetilde{Q})_{IHPF}$ and gain $(\widetilde{H}_o)_{IHPF}$ are given by;

$$(\widetilde{w}_0)_{IHPF} = \frac{1}{\sqrt{R_1R_2C_1C_2}}$$
$$(\widetilde{Q})_{IHPF} = \frac{\sqrt{R_1R_2C_1C_2}}{R_1C_1 + R_2C_2} \qquad 4.20$$
$$(\widetilde{H}_o)_{IHPF} = \left[\frac{C_3-C_p}{C_1}\right]$$

<u>Case 3</u> :-

Taking $Z_1 = R_1$, $Z_2 = R_2 + \frac{1}{sC_2}$, $Z_3 = R_3 + \frac{1}{sC_3}$, transfer function becomes :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{(R_p/R_1)[s^2R_2R_3C_2C_3 + s(R_2C_2 + R_3C_3) + 1]}{\begin{bmatrix} s^3R_2R_3R_pC_2C_3C_p + 1 \\ +s^2\begin{pmatrix} R_pR_pC_2C_3 - R_2R_pC_2C_3 \\ +R_2R_3C_2C_3 + R_2R_pC_2C_p \\ +R_3R_pC_3C_p \end{pmatrix} + s\begin{pmatrix} R_pC_2 - R_pC_3 \\ +R_2C_2 + R_3C_3 \\ +R_pC_p \end{pmatrix}\end{bmatrix}} \qquad 4.21$$

Equation (4.21) can be approximated to obtain **IBPF** :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{s^2 + s\left(\frac{R_2C_2+R_3C_3}{R_2C_2R_3C_3}\right) + \left(\frac{1}{R_2C_2R_3C_3}\right)}{sR_1\left(\frac{C_3-C_2-C_p}{R_2C_2+R_3C_3}\right)\left(\frac{R_2C_2+R_3C_3}{R_2C_2R_3C_3}\right)} \qquad 4.22$$

From equation (4.22), centre frequency $(\widetilde{w}_0)_{IBPF}$, bandwidth $(\widetilde{BW})_{IBPF}$ and gain $(\widetilde{H}_o)_{IBPF}$ are given by;

$$(\widetilde{w}_0)_{IBPF} = \frac{1}{\sqrt{R_3R_2C_3C_2}}$$
$$(\widetilde{BW})_{IBPF} = \frac{R_3C_3 + R_2C_2}{R_3C_3R_2C_2} \qquad 4.23$$
$$(\widetilde{H}_o)_{IBPF} = \frac{R_1(C_3 - C_2 - C_p)}{R_2C_2 + R_3C_3}$$

<u>Case 4</u> :-

Taking $Z_1 = R_1 \| \frac{1}{sC_1}$, $Z_2 = R_2 \| \frac{1}{sC_2}$, $Z_3 = R_3 + \frac{1}{sC_3}$, transfer function becomes :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{\left(\frac{R_p R_2}{R_1}\right)[s^2 R_1 R_3 C_1 C_3 + s(R_1 C_1 + R_3 C_3) + 1]}{\begin{bmatrix} s^2 R_2 R_3 C_3 R_p (C_2 + C_p) - sC_3 R_p R_2 + sR_2 C_2 R_p \\ + sR_3 C_3 R_p + sR_2 R_3 C_3 + sR_2 R_p C_p + (R_p + R_2) \end{bmatrix}} \quad 4.24$$

Equation (4.24) can be approximated to obtain **IBRF** :-

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{\left[s^2 + s\left(\frac{2}{R_3 C_3}\right) + \frac{1}{R_3^2 C_3^2}\right]}{\left(\frac{C_2 + C_p}{C_1}\right)\left(S^2 + \frac{1}{R_3^2 C_3^2}\right)} \quad 4.25$$

From equation (4.25), centre frequency $(\tilde{w}_0)_{IBRF}$, bandwidth $(\widetilde{BW})_{IBRF}$ and gain $(\tilde{H}_o)_{IBRF}$ are given by;

$$(\tilde{w}_0)_{IBRF} = \frac{1}{R_3 C_3}$$
$$(\widetilde{BW})_{IBRF} = \frac{2}{R_3 C_3} \quad 4.26$$
$$(\tilde{H}_o)_{IBRF} = \frac{C_2 + C_p}{C_1}$$

4.3 Error Analysis

Error in the values of cutoff frequency, quality factor and bandwidth for all four inverse filter configurations is equal to zero, i.e., independent from the effect of parasitics whereas error in the value of gain for all configurations are presented in Table 4.1 and can be calculated using equation (4.27);

$$\text{Error} = \left(\frac{\tilde{H}_o - H_o}{H_o}\right) \text{x100 \%} \quad 4.27$$

Table 4.1. Error in value of gain for inverse filters

Filter	**Error**
ILPF	R_2/R_p
IHPF	$-C_p/C_3$
IBPF	$- C_p/(C_3-C_2)$
IBRF	C_p/C_2

4.4 Sensitivity analysis

The sensitivity analysis for centre frequency ω_o, quality factor Q, and dc gain H_o for the proposed inverse filters have been determined and are presented Table 4.2.

Table 4.2. Sensitivity Analysis

Filter	Sensitivity
ILPF	$S_{R_1}^{w_o} = S_{R_3}^{w_o} = S_{C_1}^{w_o} = S_{C_3}^{w_o} = -\frac{1}{2}$ $S_{R_1}^{Q} = S_{C_1}^{Q} = \frac{R_3C_3 - R_1C_1}{2(R_3C_3 + R_1C_1)}$ $S_{R_3}^{Q} = S_{C_3}^{Q} = \frac{R_1C_1 - R_3C_3}{2(R_3C_3 + R_1C_1)}$
IHPF	$S_{R_1}^{w_o} = S_{R_2}^{w_o} = S_{C_1}^{w_o} = S_{C_2}^{w_o} = -\frac{1}{2}$ $S_{R_1}^{Q} = S_{C_1}^{Q} = \frac{R_2C_2 - R_1C_1}{2(R_2C_2 + R_1C_1)}$ $S_{R_3}^{Q} = S_{C_3}^{Q} = \frac{R_1C_1 - R_2C_2}{2(R_2C_2 + R_1C_1)}$
IBPF	$S_{R_2}^{w_o} = S_{R_3}^{w_o} = S_{C_2}^{w_o} = S_{C_3}^{w_o} = -\frac{1}{2}$ $S_{R_2}^{Q} = S_{C_2}^{Q} = \frac{R_3C_3 - R_2C_2}{2(R_3C_3 + R_2C_2)}$ $S_{R_3}^{Q} = S_{C_3}^{Q} = \frac{R_1C_1 - R_2C_2}{2(R_2C_2 + R_1C_1)}$
IBRF	$S_{R_1}^{w_o} = S_{R_3}^{w_o} = S_{C_1}^{w_o} = S_{C_3}^{w_o} = -\frac{1}{2}$ $S_{R_1}^{Q} = S_{C_1}^{Q} = \frac{R_3C_3 - R_1C_1}{2(R_3C_3 + R_1C_1)}$ $S_{R_3}^{Q} = S_{C_3}^{Q} = \frac{R_1C_1 - R_3C_3}{2(R_3C_3 + R_1C_1)}$

It may be observed from the Table 4.2 that the sensitivities with respect to all passive components are less than the magnitude of half.

CHAPTER 5

SIMULATION RESULTS

5.1 CMOS Realization of OTRA

The CMOS model of OTRA [53], implemented in PSPICE is displayed in Fig. 5.1 and using 180 nm technology, its layout in Cadence Virtuoso has been created as shown in Fig. 5.2 with W/L ratios for each transistor as indicated in Table 5.1. Supply voltages are taken to be; V_{dd} = 1.5V and V_{ss} = -1.5V. The bias current and bias voltage are taken to be 25µA and -0.5V respectively.

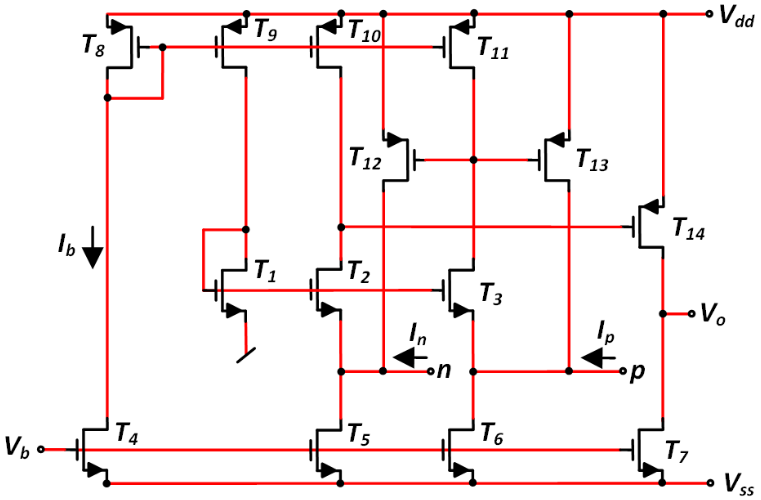

Fig. 5.1. CMOS realization of OTRA [53]

Table 5.1. W/L ratio of all transistors

Transistors	W(µm)/L(µm)
T1,T2,T3	100µm/2.5µm
T4	10µm/2.5µm
T5,T6	30µm/2.5µm
T7	10µm/2.5µm
T8,T9,T10,T11	50µm/2.5µm
T12,T13	100µm/2.5µm
T14	50µm/0.5µm

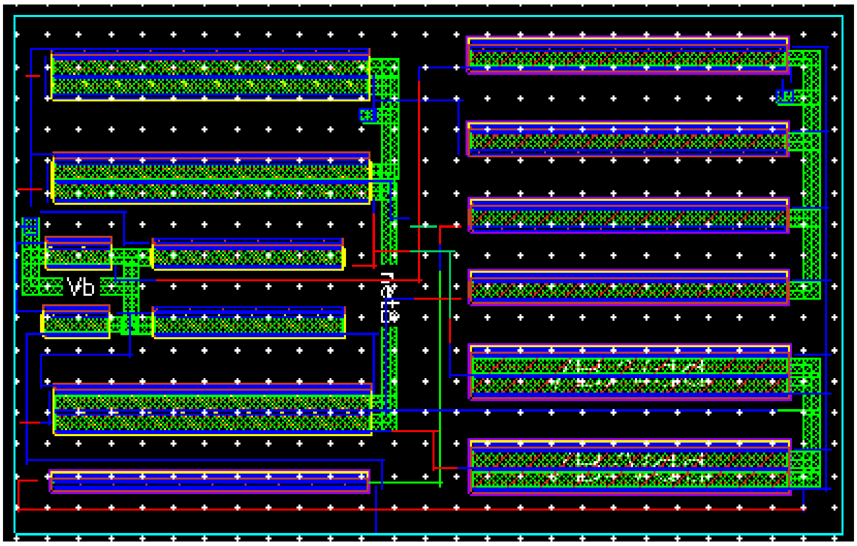

Fig. 5.2. Layout of the OTRA

5.2 Responses obtained

Table 5.2 lists the resistance and capacitance values for implementing the circuit illustrated in Fig. 4.1 at 159kHz.

Table 5.2. Values of passive components

Filter Type	Value of passive components
ILPF	$C_1 = C_2 = 0.01$nF, $R_1 = R_2 = R_3 = 100$kΩ
IHPF	$C_1 = C_2 = C_3 = 0.01$nF, $R_1 = R_2 = 100$kΩ
IBPF	$C_2 = 0.2$nF, $C_3 = 0.1$nF, $R_1 = 21.22$kΩ, $R_2 = R_3 = 7.074$kΩ
IBRF	$C_1 = C_3 = 10$pF, $C_2 = 5$pF, $R_1 = R_3 = 100$kΩ, $R_2 = 200$kΩ

The results of the simulation for the four inverse filters are displayed in Fig. 5.3, Fig. 5.4, Fig. 5.5, and Fig. 5.6.

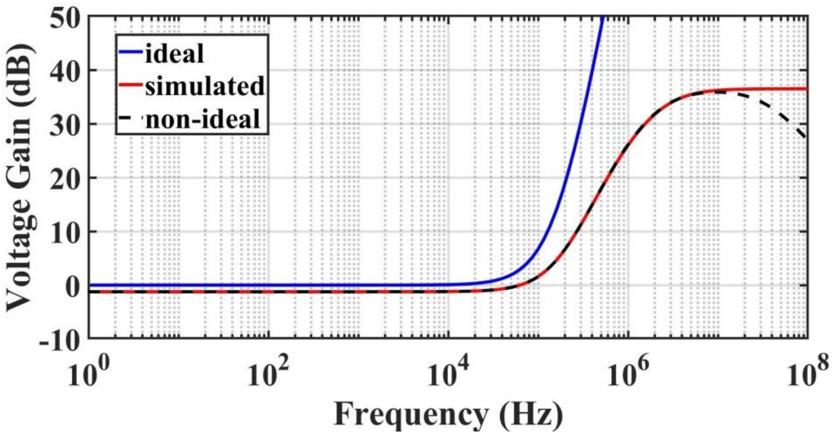

Fig. 5.3. Frequency response plot for ILPF

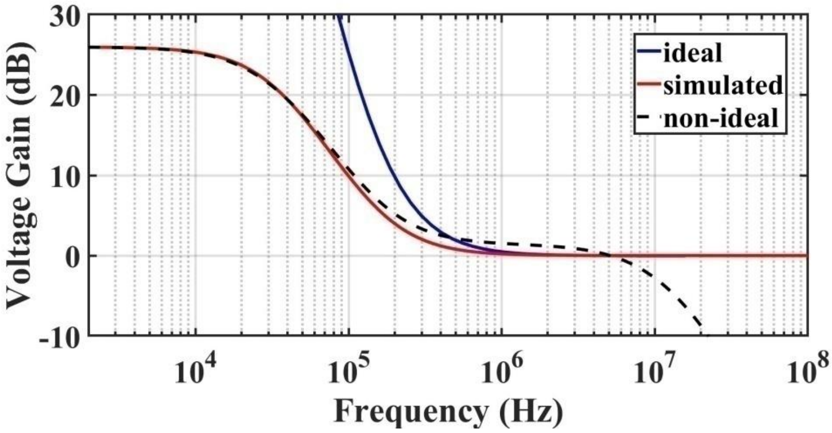

Fig. 5.4. Frequency response plot for IHPF

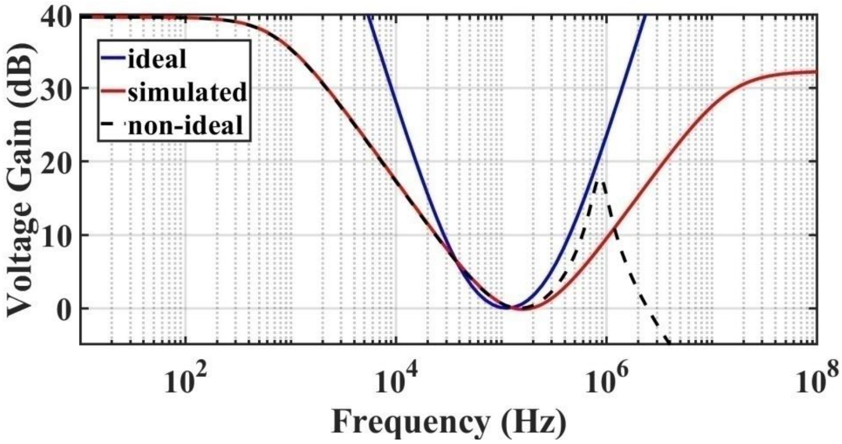

Fig. 5.5. Frequency response plot for IBPF

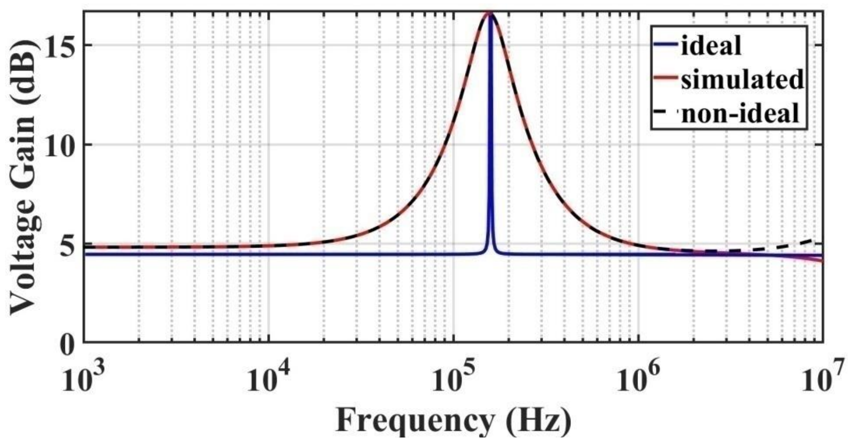

Fig. 5.6. Frequency response plot for IBRF

5.3 Noise Analysis

The noise analysis for all four inverse filters have been studied and are shown below ;

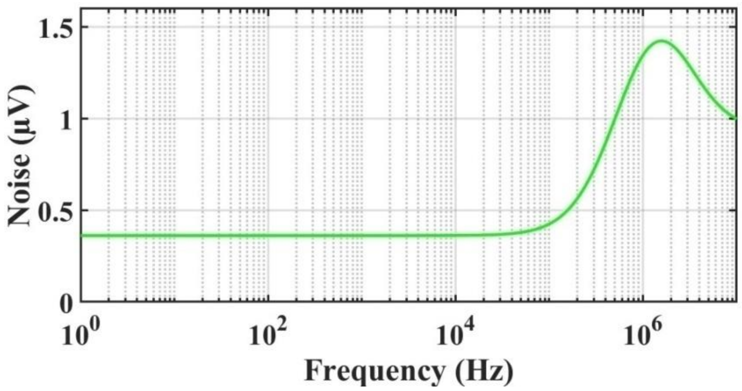

Fig. 5.7. Noise Analysis for ILPF

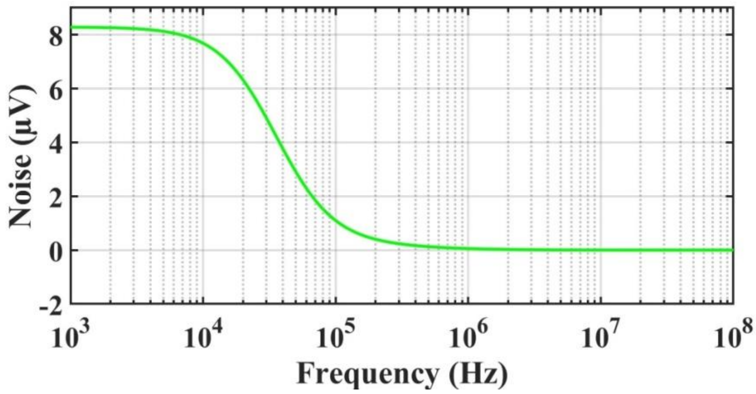

Fig. 5.8. Noise Analysis for IHPF

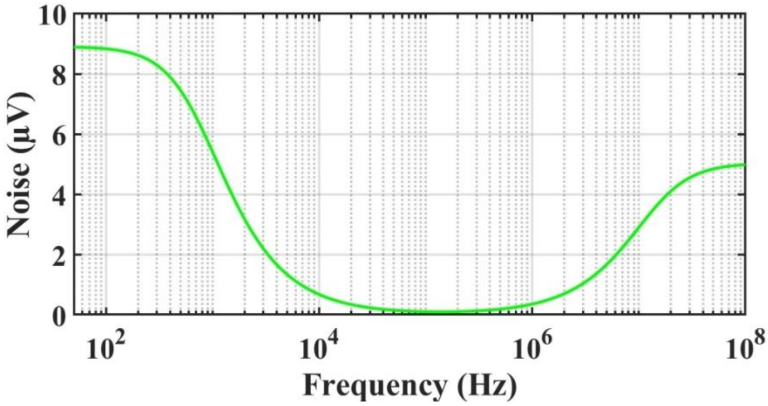

Fig. 5.9. Noise Analysis for IBPF

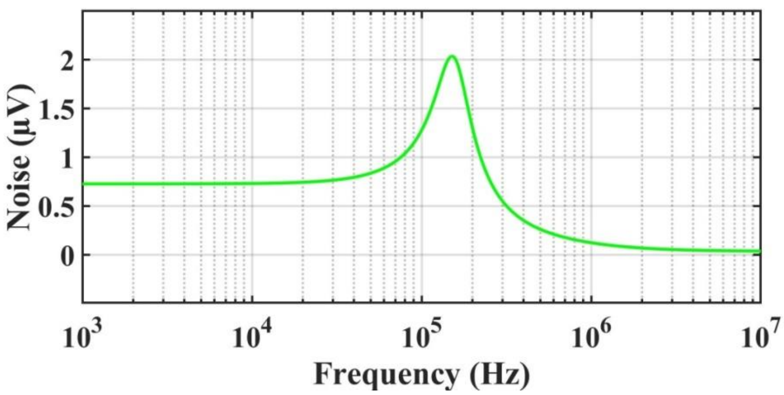

Fig. 5.10. Noise Analysis for IBRF

It has been observed that the magnitude of noise present at the output of these proposed inverse filters is quite low.

5.4 Monte carlo analysis

Monte Carlo analysis in gain and centre frequency for samples (n) = 100 along with Tolerance = 5% in all passive components is shown below ;

*n-samples=100, mean=-1.23079, minimum=-2.00746, median=-1.22976, maximum=-0.422352, n-divisions=10, sigma=0.378291, 10^{th}-percentile=-1.75432, 90^{th}-percentileile=-0.647604, 3*sigma=1.13487*

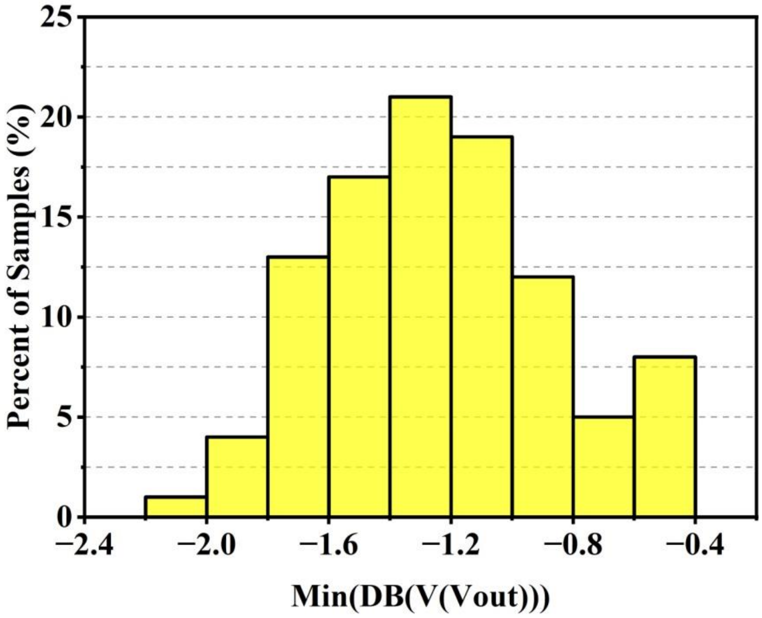

Fig. 5.11. Monte Carlo analysis for inverse low pass filter

*n-samples=100,mean=-0.01167, minimum=-0.42083, median=-0.04696, maximum=-0.440599, n-divisions=10, sigma=0.24, 10^{th}-percentile=-0.354831, 90^{th}-percentile=0.316773, 3*sigma=0.72*

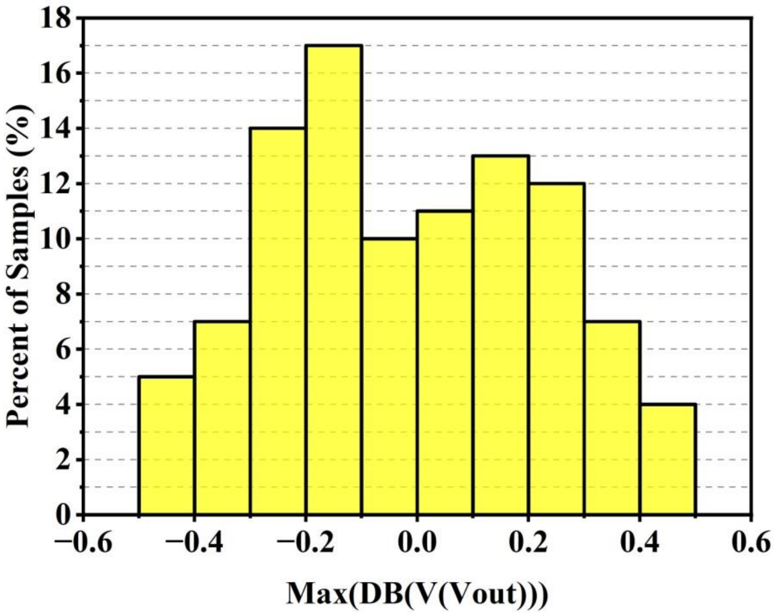

Fig. 5.12. Monte Carlo analysis for inverse high pass filter

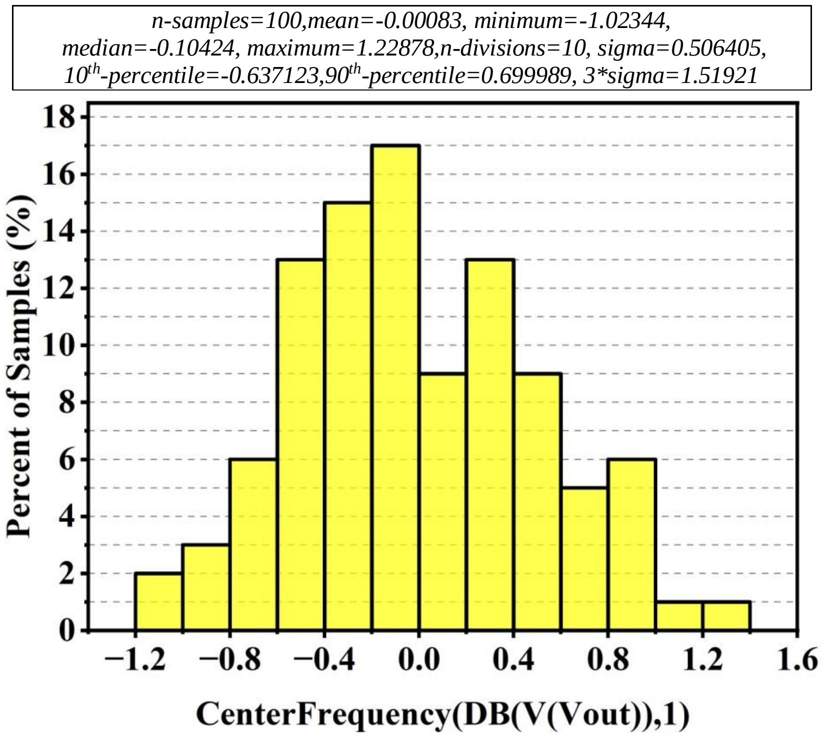

Fig. 5.13. Monte Carlo analysis for inverse band pass filter

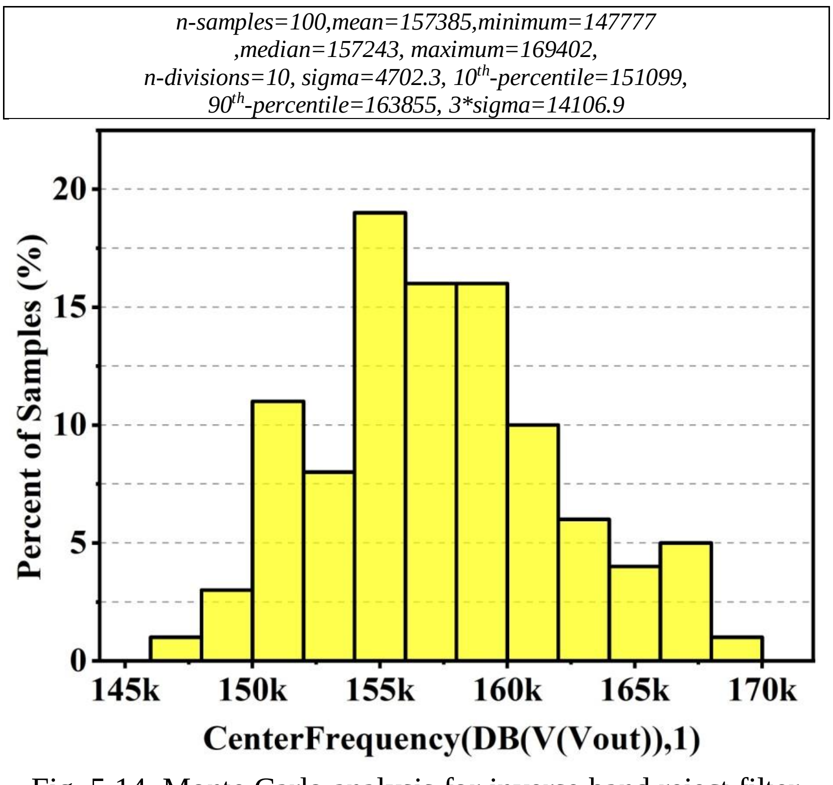

Fig. 5.14. Monte Carlo analysis for inverse band reject filter

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

This thesis describes a novel inverse filter design based on a single OTRA. Depending on the passive components used, the suggested design can produce ILPF, IHPF, IBPF, and IBRF responses. Simulations of the four inverse filters were performed using the CMOS OTRA model to verify their performance. Additional validation is performed using non-ideal analysis, noise analysis, Monte Carlo analysis, and Sensitivity analysis.

6.2 Future scope

If we observe the transfer function of IBPF, characterized by:

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{s^2 + s\left(\frac{w_o}{Q}\right) + \left(\frac{1}{w_o^2}\right)}{sH_o\left(\frac{w_o}{Q}\right)} \tag{6.1}$$

This can be depicted as follows ;

$$\frac{V_{out}(s)}{V_{in}(s)} = K_P + K_D s + \frac{1}{K_I s} \tag{6.2}$$

which, in time-domain can be expressed as ;

$$V_{out}(t) = K_P V_{in}(t) + \frac{1}{K_I} \int V_{in}(t)dt + K_D\left(\frac{dV_{in}(t)}{dt}\right) \tag{6.3}$$

Hence, it can be concluded that the IBPF is same as a PID Controller.

So, this is one example of an IBPF application that is well recognized. However, to the best of the authors' knowledge, no specific uses of other types of inverse filters have yet been recorded in the literature, with the exception of the usage of IBPF as a PID controller. As a result, applying all of the inverse filter concepts to real-world practical applications remains an unsolved and complex topic that requires further exploration.

REFERENCES

[1] A. Leuciuc, 'Using nullors for realisation of inverse transfer functions and characteristics', *Electron. Lett.*, vol. 33, no. 11, p. 949, 1997.

[2] G. Duzenli, Y. Kilic, H. Kuntman, and A. Ataman, 'On the design of low-frequency filters using CMOS OTAs operating in the subthreshold region', *Microelectronics*, vol. 30, no. 1, pp. 45–54, Jan. 1999.

[3] A. Devices, 'AD844-60 MHz, 2000 V/μs, Monolithic Op Amp With Quad Low Noise', *AD844 Data Sheet Rev. G*, pp. 1–20, 2017.

[4] A. Sedra, & K. Smith, 'A second-generation current conveyor and its applications', *IEEE Transactions on circuit theory*, 17(1), 132-134,1970.

[5] V. Stornelli, L. Safari, G. Barile, and G. Ferri, 'A new VCII based grounded positive/negative capacitance multiplier', *Int. J. Electron. Commun.*, vol. 137, no. 153793, p. 153793, Jul. 2021.

[6] R. Senani, A. K. Singh, A. Gupta, and D. R. Bhaskar, 'Simple simulated inductor, Low-Pass/band-pass filter and sinusoidal oscillator using OTRA', *Circuits Syst.*, vol. 07, no. 03, pp. 83–99, 2016.

[7] A. Ü. Keskin, 'A Four Quadrant Analog Multiplier Employing Single CDBA', *Analog Integr. Circuits Signal Process.*, vol. 40, no. 1, pp. 99–101, Jul. 2004.

[8] D. Biolek, 'CDTA-building block for current-mode analog signal processing', in *Proceedings of the 16th European Conference on Circuits Theory and Design, ECCTD'03*, vol. III, Krakow, Poland, 2003, pp. 397–400.

[9] D. Biolek, R. Senani, V. Biolková, and Z. Kolka, 'Active elements for analog signal processing: Classification, review, and new proposals', *Radioengineering*, vol. 17, pp. 15–32, 2008.

[10] E. Özer and F. Kaçar, 'Design of voltage-mode PID controller using a single voltage differencing current conveyor (VDCC)', *Analog Integr. Circuits Signal Process.*, vol. 109, no. 1, pp. 11–27, Oct. 2021.

[11] U. E. Ayten, S. Minaei, and M. Sağbaş, 'Memristor emulator circuits using single CBTA', *Int. J. Electron. Commun.*, vol. 82, pp. 109–118, Dec. 2017.

[12] P. Prakash, Y. Srivastava, S. Kumar, and A. K. Singh, 'Implementation of a Shadow Filter using CFCC', in *2021 2nd International Conference for Emerging Technology (INCET)*, Belagavi, India, 2021.

[13] S. Kumari and M. Gupta, 'Design and analysis of high Transconductance Current Follower Transconductance Amplifier (CFTA) and its applications', *Analog Integr. Circuits Signal Process.*, vol. 93, no. 3, pp. 489–506, Dec. 2017.

[14] A. Sinha, B. Aggarwal, S. K. Rai, and S. Gautam, 'Current Conveyor Transconductance Amplifier (CCTA) based Grounded Memcapacitor Emulator', *International Journal of Electrical and Electronics Research*, vol. 10, no. 3, pp. 442–446, 2022.

[15] S. V. Singh, R. S. Tomar, and D. S. Chauhan, 'Single MO-CFTA based current-mode SITO biquad filter with electronic tuning', *International Journal of Computer Science and Information Security*, vol. 11, no. 4, 2013.

[16] A. Yeşil, F. Kaçar, and K. Gürkan, 'Lossless grounded inductance simulator employing single VDBA and its experimental band-pass filter application', *Int. J. Electron. Commun.*, vol. 68, no. 2, pp. 143–150, Feb. 2014.

[17] M. E. Başak, ‘CMOS implementation of current differencing operational amplifier and its notch filter application’, *J. Circuits Syst. Comput.*, vol. 29, no. 08, p. 2050132, Jun. 2020.

[18] F. Khateb, M. Kumngern, V. Spyridon, and C. Psychalinos, ‘Differential difference current conveyor using bulk-driven technique for ultra-low-voltage applications’, *Circuits Systems Signal Process.*, vol. 33, no. 1, pp. 159–176, Jan. 2014.

[19] J. J. Burch, A. W. Green, and H. H. Grote, ‘Restoration and correction of time functions by the synthesis of inverse filters on analog computers’, *IEEE Trans. Geosci. Electron.*, vol. 2, no. 1, pp. 19–24, Nov. 1964.

[20] D. V. Kamat, ‘New Operational Amplifier based Inverse Filters’, in *2019 3rd International conference on Electronics, Communication and Aerospace Technology (ICECA)*, Coimbatore, India, 2019.

[21] N. A. Shah, and M. F. Rather, ‘Realization of voltage-mode CCII-based allpass filter and its inverse version’, *Indian J. Pure Appl. Phys.*, vol. 44, pp. 269–271, 2006.

[22] B. Chipipop and W. Surakampontorn, ‘Realisation of current-mode FTFN-based inverse filter’, *Electron. Lett.*, vol. 35, no. 9, p. 690, 1999.

[23] H.-Y. Wang and C.-T. Lee, ‘Using nullors for realisation of current-mode FTFN-based inverse filters’, *Electron. Lett.*, vol. 35, no. 22, p. 1889, 1999.

[24] T. Abuelma’atti, ‘Identification of cascadable current-mode filters and inverse-filters using single FTFN’, *Frequenz*, vol. 54, pp. 284–289, 2000.

[25] N. A. Shah, and M. A. Malik, ‘FTFN based dual inputs current-mode all pass inverse filters’, *Indian J. Radio Space Phys.*, vol. 34, pp. 206–209, 2005.

[26] R. Singh and D. Prasad, ‘Realization of Filter/Inverse Filter Topologies using single FTFNTA’, *Research Square*, Research Square, 23-Mar-2021.

[27] S. Banerjee, S. S. Borah, M. Ghosh, and P. Mondal, ‘Three novel configurations of second order inverse band reject filter using a single operational transresistance amplifier’, in *TENCON 2019 - 2019 IEEE Region 10 Conference (TENCON)*, Kochi, India, 2019.

[28] T. K. Paul, S. Roy, and R. R. Pal, ‘Realization of inverse active filters using single current differencing buffered amplifier’, *J. Sci. Res.*, vol. 13, no. 1, pp. 85–99, Jan. 2021.

[29] N. A. Shah, M. Quadri, and S. Z. Iqbal, ‘High output impedance current-mode all pass inverse filter using CDTA’, *Indian J. Pure Appl. Phys.*, vol. 46, pp. 893–896, 2008.

[30] K. Kaharwar, R. Bhagat, P. Kumar, and D. R. Bhaskar, ‘Single CMOS VCII Based Inverse Filter Configuration’, in *2023 International Conference on Modeling, Simulation & Intelligent Computing (MoSICom)*, IEEE, 2023, pp. 548–553.

[31] T. Tsukutani, Y. Sumi, and N. Yabuki, ‘Electronically tunable inverse active filters employing OTAs and grounded capacitors’, *Int. J. Electron. Lett.*, vol. 4, no. 2, pp. 166–176, Apr. 2016.

[32] A. Raj, R. Bhagat, P. Kumar, and D. R. Bhaskar, ‘Grounded-capacitor analog inverse active filters using CMOS OTAs’, in *2021 8th International Conference on Signal Processing and Integrated Networks (SPIN)*, Noida, India, 2021.

[33] S. S. Gupta, D. R. Bhaskar, R. Senani, and A. K. Singh, ‘Inverse active filters employing CFOAs’, *Electr. Eng. (Berl., Print)*, vol. 91, no. 1, pp. 23–26, Jun. 2009.

[34] S. S. Gupta, D. R. Bhaskar, and R. Senani, 'New analogue inverse filters realised with current feedback op-amps', *Int. J. Electron.*, vol. 98, no. 8, pp. 1103–1113, Aug. 2011.
[35] H.-Y. Wang, S.-H. Chang, T.-Y. Yang, and P.-Y. Tsai, 'A Novel Multifunction CFOA-Based Inverse Filter', *Circuits Syst.*, vol. 02, no. 01, pp. 14–17, 2011.
[36] K. Garg, R. Bhagat, and B. Jaint, 'A novel multifunction modified CFOA based inverse filter', in *2012 IEEE 5th India International Conference on Power Electronics (IICPE)*, Delhi, India, 2012.
[37] V. Patil and R. K. Sharma, 'Novel inverse active filters employing CFOAs', *International Journal for Scientific Research & Development*, vol. 3, no. 7, pp. 359–360, 2015.
[38] A. K. Singh, A. Gupta, and R. Senani, 'ERRATA: OTRA-Based Multi-Function Inverse Filter Configuration', *Adv. Electr. Electron. Eng.*, vol. 16, no. 1, Apr. 2018.
[39] A. Pradhan and R. K. Sharma, 'Generation of OTRA-based inverse all pass and inverse band reject filters', *Proc. Nat. Acad. Sci. India Sect. A*, vol. 90, no. 3, pp. 481–491, Sep. 2020.
[40] R. Pandey, N. Pandey, T. Negi, and V. Garg, *CDBA based universal inverse filter. International Scholarly Research Notices*. 2013.
[41] A. R. Nasir, and S. N. Ahmad, 'A new current-mode multifunction inverse filter using CDBAs', *Int. J. Comput. Sci. Inf. Secur.*, vol. 11, pp. 50–53, 2013.
[42] R. Bhagat, D. R. Bhaskar, P. Kumar, 'Inverse Band Reject and All Pass Filter Structure Employing CMOS CDBAs', *Int. J. Eng. Res. Technol*., vol. 8, pp. 39–44, 2019.
[43] R. Bhagat, D. R. Bhaskar, and P. Kumar, 'Multifunction filter/inverse filter configuration employing CMOS CDBAs', *Int. J. Recent Technol. Eng*, vol. 8, no. 4, pp. 8844–8853, 2019.
[44] S. S. Borah, A. Singh, and M. Ghosh, 'CMOS CDBA Based 6 th Order Inverse Filter Realization for Low-Power Applications', in *2020 IEEE REGION 10 CONFERENCE (TENCON)*, IEEE, 2020, pp. 11–15.
[45] P. Kumar, N. Pandey, and S. K. Paul, 'Realization of resistorless and electronically tunable inverse filters using VDTA', *J. Circuits Syst. Comput.*, vol. 28, no. 09, p. 1950143, Aug. 2019.
[46] P. Kumar, N. Pandey, and S. K. Paul, 'Electronically tunable VDTA-based multi-function inverse filter', *Iran. J. Sci. Technol. Trans. Electr. Eng.*, vol. 45, no. 1, pp. 247–257, Mar. 2021.
[47] M. A. Al-Absi, 'Realization of inverse filters using second generation voltage conveyor (VCII)', *Analog Integr. Circuits Signal Process.*, vol. 109, no. 1, pp. 29–32, Oct. 2021.
[48] S. M. Al-Shahrani and M. A. Al-Absi, 'Efficient inverse filters based on second-generation voltage conveyor (VCII)', *Arab. J. Sci. Eng.*, vol. 47, no. 3, pp. 2685–2690, Mar. 2022.
[49] R. Senani, D. R. Bhaskar, and A. Raj, 'Inverse analog filters: History, progress and unresolved issues', *Electronics (Basel)*, vol. 11, no. 6, p. 841, Mar. 2022.
[50] J. Nako, C. Psychalinos, and S. Minaei, 'Single-input multiple-output inverse filters designs with cascade capability', *Int. J. Electron. Commun.*, vol. 175, no. 155061, p. 155061, Feb. 2024.
[51] J. J. Chen, H. W. Tsao, S. Liu and W. Chui, 'Parasitic-capacitance-insensitive current-mode filters using operational transresistance amplifiers', *IEE Proc.*

Circuits Devices and Systems 1995, vol. 142, no. 3, p. 186–192, 1995.

[52] K. N. Salama and A. M. Soliman, 'CMOS operational transresistance amplifier for analog signal processing', *Microelectron J. 1999*, vol. 30, issue 3, p. 235–45, 1999.

[53] H. Mostafa and A. M. Soliman, 'A modified CMOS realization of the operational transresistance amplifier (OTRA)', *Frequenz*, *60(3-4)*, pp. 70-77, 2006.

PAPER NAME

VISHWAJIT_DISSERTATION_MTECH.pdf

AUTHOR

VISHWAJIT YADAV

WORD COUNT

5083 Words

CHARACTER COUNT

25457 Characters

PAGE COUNT

36 Pages

FILE SIZE

1.8MB

SUBMISSION DATE

May 28, 2024 8:39 PM GMT+5:30

REPORT DATE

May 28, 2024 8:40 PM GMT+5:30

● 13% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

- 11% Internet database
- 7% Submitted Works database
- 0% Publications database

● Excluded from Similarity Report

- Crossref database
- Bibliographic material
- Small Matches (Less then 8 words)
- Crossref Posted Content database
- Cited material

13% Overall Similarity

Top sources found in the following databases:

- 11% Internet database
- 0% Publications database
- 7% Submitted Works database

TOP SOURCES

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

1	hdl.handle.net Internet	2%
2	mdpi.com Internet	1%
3	researchgate.net Internet	1%
4	dspace.dtu.ac.in:8080 Internet	1%
5	Malaviya National Institute of Technology on 2013-04-30 Submitted works	<1%
6	link.springer.com Internet	<1%
7	ijitee.org Internet	<1%
8	Indian School of Mines on 2015-12-23 Submitted works	<1%
9	ijesrt.com Internet	<1%

10	moam.info Internet	<1%
11	vdocuments.mx Internet	<1%
12	Birla Institute of Technology on 2018-07-06 Submitted works	<1%
13	etd.aau.edu.et Internet	<1%
14	iGroup on 2014-07-21 Submitted works	<1%
15	cigre-ngn-uk.org Internet	<1%
16	patents.justia.com Internet	<1%
17	midem-drustvo.si Internet	<1%
18	University of Liverpool on 2010-05-05 Submitted works	<1%
19	University of the West Indies on 2015-04-15 Submitted works	<1%
20	acikbilim.yok.gov.tr Internet	<1%
21	National Institute of Food Technology Entrepreneurship and Managem... Submitted works	<1%

22	SAMRAT ASHOK TECHNOLOGICAL INSTITUTE VIDISHA M.P on 2020-... Submitted works	<1%
23	dokumen.pub Internet	<1%
24	mafiadoc.com Internet	<1%
25	visionics.co.in Internet	<1%
26	radioeng.cz Internet	<1%